WATER QUALITY MODELING STUDY FOR UMHLANGANE RIVER, SOUTH AFRICA

A DISSERTATION SUBMITTED TO THE

COLLEGE OF AGRICULTURE, ENGINEERING AND SCIENCE

OF

UNIVERSITY OF KWAZULU NATAL

BY

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE

OF

MASTER OF SCIENCE

IN

ENVIRONMENTAL ENGINEERING

MAY 2016

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Declaration

Supervisor:

As the candidate's Supervisor I agree/do not agree to the submission of this dissertation.

Signed:…….(Dr Muthukrishna vellaisamy Kumarasamy) Date:..……

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ACKNOWLEDGMENTS

I would thank the God for his grace and blessings in completing this work successfully. I would like to thank my supervisor Dr Muthukrishna vellaisamy Kumarasamy for his expert guidance and motivation. My deepest gratitude goes to my family for their motivation, continuous support and prayers.

Abstract

Over the past few decades, river water quality has been a critical issue in many parts of the world due to various domestic, industrial and agricultural pollutants. The challenge lies in developing mechanisms and tools, that will assist us to mitigate, prevent or possibly reverse deteriorating river water quality. Water quality models are the most useful tools in describing river ecological conditions, assessing effects of water pollution and assisting decision makers for water quality management. They can be used to predict the changes of the water quality parameters like Dissolved Oxygen (DO), Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), etc. They also contribute in reducing the cost of labour and time needed to conduct field studies or experiments to some degree. One of the well-known water quality models is the Hydrologic Engineering Centre River Analysis System (HEC-RAS).

This study aimed to assess pollutant transport characteristics of Umhlangane River north of Durban using the HEC-RAS model. Hydraulic outputs were produced by executing the hydraulic model for each defined point in time. The water quality simulation was obtained from the HEC-RAS model with modelled hydraulic data as inputs. The Hybrid Cells in Series (HCIS) model is a conceptual mixing cells based water quality model that has an advantage over the Fickian based advection dispersion equation model (ADE). An impulse response of the HCIS model matches with the same of the ADE, when the Peclet number is more than four. The HCIS model produced reasonable results in terms of percentage error when compared with actual recorded data. The simulation results of BOD and COD tend not to vary with time unlike the observed results due to average constant input of pollutants. A main advantage with this model is that it deals with first order ordinary differential equation and which can accommodate any reaction kinetics without any complexity in model equation unlike the ADE model. Thus this study aimed to derive a model component for the HCIS and investigated its ability to simulate water quality parameters such as BOD, COD and DO under predefined condition. The proposed model in this study yielded positive outcome at the upper reach of Umhlangane River with an average agreement between simulation results and the observed data. The work is concluded by rendering a future potential scope of the HCIS to incorporate nutrient dynamics and non-point source pollution.

Key words: HCIS, HECRAS, Umhlangane River, Peclet number, Dissolved Oxygen, Chemical Oxygen Demand, Biochemical Oxygen Demand

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Nomenclature

k_1= the BOD degradation rate constants

k_1' = the COD degradation rate constants

k_2 = the atmospheric reaeration constant

A = cross sectional area of the flow

D_0= the boundary deficit of dissolved concentration

S_{DO} = saturated DO concentration

Q = inflow

x = distance along channel

t = time

V = volume of the water quality cell (m^3)

V_1 is the volume of the first thoroughly mixed zone

V_2 is the volume of second thoroughly mixed zone

α= the residence time in the plug flow zone

T_1= the residence time of the fluid in the first thoroughly mixed zone

T_2= the residence time of the fluid in the second thoroughly mixed zone

D_x = dispersion coefficient (m^2/s)

S_L = source or sink representing direct and diffuse loading rate ($g\ m^{-3}s^{-1}$)

C = concentration of a constituent (g/m^3)

S_B= source or sink representing boundary loading rate for upstream, downstream, and benthic interaction ($g\ m^{-3}s^{-1}$)

S_K= source or sink representing biogeochemical reaction rate ($g\ m^{-3}s^{-1}$)

C_{n+1} = concentration of a constituent at present time step (g/m^3)

C_{up}^* = QUICKEST concentration of a constituent at upstream (g/m^3)

C_n = concentration of a constituent at previous time step (g/m^3)

C_{up}^* = QUICKEST derivative of a constituent at upstream (g/m^4)

D_{up}= upstream face dispersion coefficient (m^2/s)

V_n = volume of the water quality cell at previous time step (m^3)

V_{n+1} = volume of the water quality cell at present time step (m^3)

Q_{up} = upstream face flow (m^3/s)

A_{up} = upstream face cross section area (m^2)

SS = total source and sink terms of a constituent ($g/m^3/s$)

CHAPTER ONE

INTRODUCTION

1.1 Background

Water plays an important role in the sustainability of all living beings and in meeting various domestic, agricultural and industrial demands. The increasing scale of water scarcity associated with water pollution problems, has turned water quality management into a pressing issue. Degrading water quality over the past decades has been a serious concern due to the rapidly growing population, resources abuse and industrial revolution (Gupta *et al*., 2009), and also by scientific, human and technological developments (Oiste & Breaban, 2012). It needs to be realised that when water quality conditions worsen, the quantity of water available for usage decreases; however the human dependence on this natural resource remains the same (Young & Beck, 1974).

The consequence of long term water pollution is a lack of availability and inadequacy of clean and safe water in many countries around the world (Das & Panda, 2010). The negative repercussions of water pollution continue to be experienced by the environment and human; it was reported that millions of people die every year as a consequence of water related diseases (WHO, 2007; Tumwine *et al*., 2012). The main sources of water that are constantly being impaired by pollutants are largely rivers, streams, lakes and underground water. Despite rivers being a major source of water supply, they are commonly used as the primary disposal route for waste water (Bartram & Balance, 1996). The contamination of the river by pollutants may lead to serious and costly consequences that might be impossible or difficult to reverse. To improve, protect and to avoid the ecosystem of our water sources being destroyed further, various preventative measures need to be devised. When employing suitable water quality management strategies having limited amount of field data is not feasible, modelling studies are often used to address water pollution problems and to design effective mitigation measures (Chapra, 1997).

In order to understand and develop water quality models, it is vital to acquire knowledge about pollutants and pollutant transport processes. The pollutants' source could be point or non-point sources. Point pollution is a type of a pollution that comes from a single or exclusive location, for example sewerage outfalls and waste streams. The quantities of pollutants emanating from these sources are known from field data measurements (Carpenter *et al.*, 1998). Non point, also known as diffuse pollution, arises where the sources are difficult to identify. This includes rainfall, runoff from settlements, roads, agricultural activities, and construction sites (Almeida, 1998). The

harmful effects of this type of pollution often arise from the accumulation of different sources and are difficult to regulate (Chansheng & DeMarchi, 2009).

Pollutants originating from various sources can be divided into: conservative and non-conservative pollutants. Those pollutants that do not degrade with time, but may change their form are known as conservative pollutants and non-conservative pollutants are those that degrade in the receiving water (Allen, 2015). The Biochemical Oxygen Demand (BOD), Dissolved Oxygen (DO), Temperature, Total Dissolved Solids (TDS) and Chlorides are some of the important water quality indicators of pollution. Temperature, TDS and Chloride are characterised as being conservative by nature; temperature is a catalyst of non-conservative pollutants such as BOD and DO (Smith, 1980). Pollutants undergo several processes when they are injected into rivers. Among these are advection and diffusion processes. The pollutants are advected by the moving water and at the same time disperse in all directions whilst under turbulent diffusion (Fischer, 1967, 1968; Chatwin, 1970, 1971). In addition, some fractions of the pollutant are absorbed during pollutant transport by the stream bed. The process is reversed once the concentration of pollutant in stream water is lower than that in bed sediments. These two interrelated processes are known as adsorption and desorption respectively (Smith, 1980).

Pollutant transport processes are in essence three-dimensional, but it has been argued by many researchers (Fischer, 1967, 1968; Chatwin 1970, 1971) that they can be adequately represented or analysed by one-dimensional process in a longitudinal direction. The advection dispersion equation (ADE) model is one of the most widely used model for dealing with solute transport challenges. The argument is also owed to the limiting assumptions of the ADE model and estimation difficulties of its parameters (Day, 1975; Chatwin, 1980; Chatwin & Allen, 1985; Young & Wallis, 1993). The other models like Cells in Series (CIS) and Aggregated Dead Zone (ADZ) came into play because of the practical limitations and applications of the ADE model for the natural rivers (Young &Wallis, 1993; Fischer, 1967, 1968; Sooky, 1969; Day & Wood, 1969; Fischer *et al*., 1979; Chatwin, 1980; Chatwin & Allen, 1985; Van Genuchten & Jury, 1987). Although there were some improvements brought by these alternative models, concerns were also raised about the inadequate advection in the concentration-time (C-t) profile produced by CIS and difficulties with the estimation of ADZ model coefficients. The shortcomings of the CIS and ADZ models were addressed by using the Hybrid Cells in Series (HCIS) model (Ghosh, 2001; Ghosh *et al*., 2004). This model has been conceptualised with a plug flow zone and two thoroughly mixed zones of unequal residence time connected in series in order to simulate advection dispersion pollutant transport. As HCIS model has a potential to adequately reproduce

the impulse response (Ghosh, 2001; Ghosh *et al*., 2004; 2008); it was further improved by considering pollutant decay (Kumarasamy et al., 2013; Kumarasamy, 2015)

In addition, there are numerous water quality models available: Soil Water and Analysis Tools Model, Water Quality Analysis Simulation Program, MIKE 11, QUALs, the Hydrologic Engineering Centre River Analysis System and many others. The knowledge acquired from these models can be used to equip water managers with proper tools that will assist them to make reasonable water quality predictions and prevent further contamination in our rivers (Wang *et al*., 2013). The use of a suitable model is a common practice for showing the cause and effect of the relationship between pollutants emissions and water quality (Mannina & Viviani, 2010). This is also best addressed by improving the shortcomings of the existing models. Thus, there is a scope for continuous development of water quality models to assess water quality status.

1.2 Motivation

The Umhlangane River is one of the rivers, as shown in Figure. 1.1, situated north of Durban that is characterised by poor water quality. This has been declining over the years due to commercial, industrial, and residential activities taking place around it. This river has a sub-catchment of 12240ha and is located in a relatively flat coastal plain upstream and north of the uMgeni estuary.

Figure 1.1 Map of the Umhlangane River (Ethekweni Municipality, 2015a)

This research aims to study the pollutant transport characteristics of the Umhlangane River using the Hydrologic Engineering Centre River Analysis System (HEC-RAS) model and the Hybrid Cells in Series model (HCIS). It is proposed that both models be used to assist in water quality management of this river by modelling some of the important water quality parameters such as BOD, COD and DO. Over the past decades, various components and variables affecting water quality have been gradually integrated into water quality models following the evolution of water quality problems. Therefore an attempt will be made in this study to enhance the water quality modelling capabilities of the Hybrid Cells in Series model by incorporating BOD and COD into the model. The HCIS model was proven to be flexible for further improvement by resolving some of the deficiency associated with the Aggregated Dead Zone, Advection Dispersion Equation, and the Cells in Series models (Ghosh, 2001; Ghosh *et al.*, 2004; 2008).

1.3 Focus and Purpose of Study

The study will endeavour to simulate pollutant transport characteristics of the Umhlangane River north of Durban using Hydrologic Engineering Centre River Analysis System. An attempt will also be made to modify to the Hybrid Cells in Series to simulate pollutant transport considering decay of pollutants and dissolved oxygen re-aeration processes.

1.4 Research Questions

How is the Hydrologic Engineering Centre River Analysis System model useful in assessing water quality of the Umhlangane River?

Is the modified Hybrid Cells in Series model (developed in this study) capable of simulating water quality (BOD, COD and DO) of the Umhlangane River?

1.5 Research Objectives

(i) To analyse the water quality status of the Umhlangane river.

(ii) To use the HEC-RAS model to represent accurately the hydrodynamics and water quality (BOD, COD and DO) of Umhlangane River.

(iii) To investigate and test the modified HCIS model's abilities to model water quality parameters.

1.6 Overview of the Chapters:

Chapter One: gives the overall view introduction of the present study and background on pollution, and pollutants.

Chapter Two: provides an extensive examination of the literature investigating some of the important water quality indicators (Dissolved Oxygen, Biochemical Oxygen and Chemical Oxygen) and effects by pollutants on water bodies. It also provides insight on different stages that were undergone by water quality models and their application difficulties. The advection dispersion model is also presented including some of the alternative mixing in cells series models.

Chapter Three: presents a detailed description of the HEC-RAS model and formulation of the modified HCIS models and the various parameters inputs required.

Chapter Four: the methodology description of the study area, analysis of the collected data and the how the reaches for the entire river are divided for both models.

Chapter Five: presents the results and discussion produced by the two models (HEC-RAS and HCIS) reach by reach of concentrations in the water quality parameters compared to the observed data. It also presents the findings on HCIS‘s abilities as developing model.

Chapter Six: provides conclusions from the findings of the present study and recommendations for future work.

CHAPTER TWO

LITERATURE REVIEW

2.1 Background on Water Pollutants

Pollutants are defined as any substance that decreases or worsens the state of quality of a body of water. The presence (or traces) of pollutants in water bodies may disqualify it for its intended usage. Due to urbanisation and industrialisation, the number of pollutants' load sources has increased many ways (Kumarasamy, 2007). This has led to a state of affairs where water quality is worsening; hence the self-purification ability of water dealing with these pollutants is limited. Pollutants can be classified as organic, inorganic, pathogens, nutrients and agriculture runoff, suspended solids and sediments, thermal and radioactive pollutants that pose environmental and health hazards (Ghangreka, n.d.). Their classifications refer only to the harmful effects to be expected based on source and composition. They do not provide much perspective into water quality and the complex processes that are involved when pollutants are discharged into water bodies. In order to better understand these processes, particularly from an ecosystem point of view, it is important to recognise the difference between biodegradable and non-degradable pollutants and their sources (Odum, 1971).

Pollutants can be further classified as being either non-conservative or conservative when emphasising their occurrences within the receiving water body. Conservative pollutants are those substances that are not altered by biological or chemical processes that occur in water over time within a given system. Recycling techniques provide more efficient ways of minimising the quantities of conservative substances released in waste waters. Non-conservative pollutants are those substances that change in form or quantity by biological, physical and chemical phenomena. These substances are oxidised and decomposed by natural processes when received in water bodies (Bai *et al.*, 2012). The most widespread source of such organic pollutants is from domestic waste and is easily biodegradable. The majority of pollutants that are discharged into rivers are inorganic chemicals, which are diluted based on a number of factors (Chanlett, 1973). Monitoring water quality is an essential measure in understanding the behaviour of water pollutants and for devising effective mitigation strategies (Jun Li *et al.*, 2012). The traditional importance of measuring pollutants concentration in a river is to determine their influence on dissolved oxygen (DO). In general, pollutants are measured according to their oxygen demand, which is biochemical oxygen demand (BOD) or chemical oxygen demand (COD). These parameters are relatively convenient to measure, and permit regional and global comparisons (Chapra, 1999).

2.2 Self-Purification

In order to achieve and maintain good water quality for a river system, it is important to understand ways of self-purification and governing pollution processes (Odum, 1971; Chanlett, 1973). The self-purification process depends on a wide range of parameters. For example, if water is not overloaded with pollutants, an aerobic process will take place and no unpleasant odour will be produced. However, if heavily loaded with pollutants, the biological process becomes anaerobic (i.e. bacteria not utilising free oxygen) producing noxious gases that could be harmful to life (Unesco and WHO, 1978). The relation between biological, chemical and physical processes is critical in predicting the impact of an effluent on a river. Figure 2.1 and 2.2 demonstrate the effects of organic pollutants on a river and the changes taking place downstream from the pollution point source. When organic pollutants are discharged into a water body depletion of dissolved oxygen occurs. This is because of the high demand for oxygen by the bacteria responsible for decomposing the pollutants (Clark, 1996).

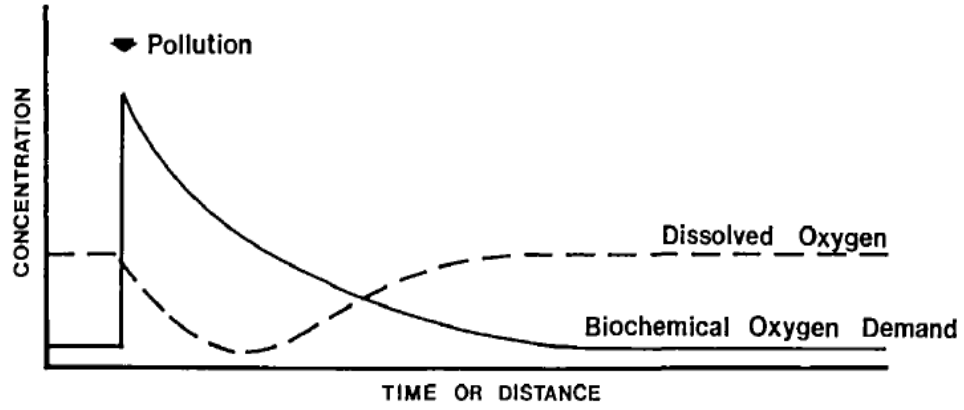

Figure 2.1 Dissolved and Biochemical Oxygen Demand - Concentration vs Time or Distance (Unesco and WHO, 1978)

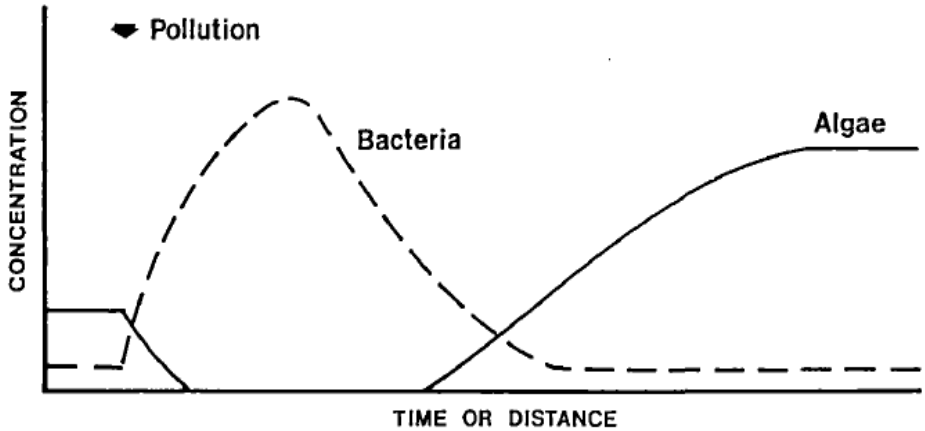

Figure 2.2 Bacteria and Algae - Concentration vs Time or Distance (Unesco and WHO., 1978)

2.3 Effect of Pollutants on a water body – dissolved oxygen

Dissolved oxygen (DO) serves as an important indicator in assessing water quality because of its influence on aquatic life. It refers to the amount of free, non-compound oxygen present in water. DO is generated by diffusion of oxygen from the atmospheric air into water and production of oxygen from photosynthesis by aquatic plants (Water Action Volunteers, 2006). Diffusion from the atmosphere is a relatively slow process, but it is responsible for most of the dissolved oxygen in our rivers. Extreme low levels of dissolved oxygen can endanger aquatic life by hampering animals and plants' survival in water. It may lead to unhealthy and less biologically diverse aquatic communities (Lindenschmidt, 2005).

When organic matter enters a river, it acts as a source of energy for decomposer microorganisms in the water. This energy surplus leads to exponential growth of the bacteria population in the decomposers, and microorganisms consume dissolved oxygen through respiration. As their population increases, more dissolved oxygen is consumed. The population will start to die off at some point when the organic material is depleted (Lindenschmidt, 2005). Theoretically, the microorganisms proceed to die off until there are no oxygen-demanding substances left. It is clear that the degradation of organic matter in the presence of bacteria leads to reduction in the level of oxygen and also the introduction of excess organic matter may result in a total depletion of oxygen (Turkar *et al*., 2011). Unpolluted fresh water varies greatly in the concentration of dissolved oxygen; it is influenced by temperature, atmospheric pressure, and salinity. Atmospheric pressure and water temperature affect the ability of water to retain dissolved oxygen. Warm water at low atmospheric pressure holds less dissolved oxygen than cold water at high atmospheric pressure. Oxygen levels are also affected by the degree of water turbulence or wave action and level of light penetration as well as turbidity, colour and water depth (Water Action Volunteers, 2006).

The utilities such as wastewater treatment works that are built along the rivers to reduce level water deterioration sometimes create water quality problems. The use of chloramines for disinfection can result in excessive growth of nitrifying bacteria. The continuous oxidation of nitrites into nitrates (Figure C5 in Appendix C,) and of ammonia into nitrites by autotrophic bacteria can result in serious negative effects in water bodies (Wolfe *et al.*, 1988; Cunliffe, 1991). Another cause of water quality changes in water is orthophosphate (Figure C6 in Appendix C). It is found in wastewater and naturally as Phosphates anion. It is essential for photosynthesis, plant growth, and microorganisms and animals. If discharged in large quantities it may stimulate the growth of aquatic organisms in an undesirable manner (Smith *et al*., 1999). Therefore testing and

removal of phosphorus from effluent released into our rivers is critical to these rivers' water quality. The effect of acid deposition can also be harmful to most aquatic systems if it is lower than 6, particularly when less than 5. The pH (Figure C4 in Appendix C), oxygen and alkalinity reduction is a result of chloramine residuals that increase in heterotrophic bacteria by autotrophic creation of soluble microbial products (Odell *et al*., 1996).

The high level of nutrients produced above the levels of their consumption increases biological oxygen demand at bottom layer of the water column where density stratification interferes with reaeration (Breitburg *et al.*, 2003). The dissolved sag curve demonstrates how the DO concentration in a volume of water changes with time and distance after organic material is introduced into water. The changing concentration of DO in a river after the introduction of organic material is shown in Figure 2.3. DO Sag was developed by Burke in the late 1980s (Cathey, 1997). The model is based on a modified version of the Streeter and Phelps equation. The majority of DO models including DO sag is based on the concept of the dissolved oxygen sag curve and the Streeter and Phelps equation. As oxygen is being consumed by the decomposers, the river is also reaerated by the flux of oxygen from the atmosphere into the water. The concentration of DO will increase until it reaches atmospheric equilibrium when the oxygendemand is less than the reaeration rate (Brown, 1995). When the oxygen demand is greater than the reaeration rate, the concentration of DO will decrease.

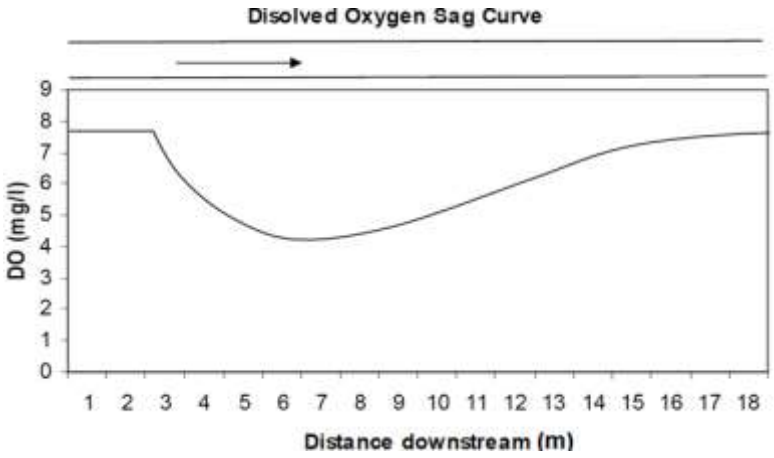

Figure 2.3 Dissolved Oxygen Sag Curve (Cathey, 1997).

2.4 Development of Water Quality Models

Water quality models are often employed as important tools in water quality management as a number of researchers carried out some studies in the last decades to develop models to deal with quality problems (Pallottino *et al.*, 2005; Wang & Huang 2011; Wang *et al*., 2012). The ultimate goal of water quality modelling is to assist water quality managers to make appropriate decisions to prevent further pollution of water resources. Reasonable predictions of water quality parameters by water quality models help to ensure safe prescribed water quality standards. Selection of suitable models and parameters determines the influence of simulation results and accuracy of water quality assessments. Since 1925, many water quality models have been formulated and applied to predict water quality of rivers, lakes and estuaries successfully (Chihhao Fan *et al.*, 2012). The majority of water quality models have focused on predicting dissolved oxygen concentrations in rivers. This tradition still forms an important foundation for water quality assessments (Lindenschmidt, 2005).

The Streeter and Phelps equation is one of the first one-dimensional water quality simulation models. It was first produced by Streeter and Phelps in 1925 to simulate the dissolved oxygen (DO) deficit of the Ohio River in United States (Jun Li *et al*., 2012). The model was based on the assumption that the decay rate is of a first order. The equation considers the total biochemical oxygen demand decay and atmospheric reaeration under the assumption of a uniform flow velocity and steady state conditions. The key assumption used in the derivation of Streeter and Phelps model is that there is no organic carbon flux across the boundaries of each unit volume of water and no oxygen is added except that due to reaeration. In this model, K_1 represents the rate of oxygen consumption due to oxidation of organic matter and other reduced substances. The reaeration coefficient K_2 represents the rate of oxygen input to the river and is influence by flow rate, water depth, turbulence, water temperature, and degree of water column oxygen

$$\frac{dD}{dt} = k_1 L - k_2 D \quad (2.1)$$

$$L = L_0 e^{-k_1 t} \quad (2.2)$$

After substituting Eq. 2.2 into Eq. 2.1, the DO deficit may be solved and the Streeter and Phelps equation results in:

$$D = \frac{k_1 L_0}{k_1 - k_2} . (e^{-k_1 t} - e^{-k_2 t}) + D_0 . e^{-k_2 t} \quad (2.3)$$

where

D_0 = initial DO deficit.

D = the DO deficit

k_1= the BOD degradation constant

k_2 = the atmospheric reaeration constant,

L = the BOD concentration,

L_0 = the ultimate BOD, and

t = the hydraulic retention time.

After 1925 there have been continuous attempts to develop new and better water quality models to address the Streeter and Phelps model's original limitations. The modifications of Streeter and Phelps model still remain among the most widely used models (Gotovtsev, 2010). The water surface quality models have undergone three important stages in development (Wang *et al*., 2013). The first stage primary stage was from 1925 to 1965 where the Streeter and Phelps models were modified and further developed. The focus was on interactions among different components of water quality in river systems, such as hydrodynamic transmission, sediment oxygen demand, and algal photosynthesis and respiration. The models of this period were one dimensional steady-state models and based on BOD-DO modelling; they were successfully applied in water quality prediction (O'Connor, 1967).

The second was an improvement stage with rapid model development between 1965 and 1995. Before 1975, not only elements other than dissolved oxygen were included. This included other elements such as phytoplankton and zooplankton. Different systems and the relationships between biologic growth rate and nutrients, sunlight and temperature were also taken into account (Liou *et al*., 2003; Xiao *et al.*, 2012). These models were also expanded to two-dimensional models. According to Post (1975), three-dimensional models were developed and sediments became an important element to be considered in the interaction processes of these models (Bai *et al*., 2012). The third stage after 1995 has been a broadening or deepening stage. Pollution models were developed to help control the pollution sources (Wang *et al*., 2004). However, the wet and dry atmospheric deposition such as nitrogen compounds, and heavy metals showed increasing effects on water quality of rivers.

2.5 Advection Dispersion Equation

The solute transport process in rivers and streams relies on chemical, physical, and biological properties of the pollutants as well as mixing mechanisms. The whole phenomenon is basically assembled on advection and diffusion processes (Fischer *et al.*, 1979; Elhadi *et al.*, 1984; Rutherford, 1994). In 1855, Adolph Fick developed the relationship between heat transfer and molecular diffusion by using Fourier‘s law. The diffusion theory for fluids with uniform flow was further developed by Taylor in 1921 and later on, in 1953 and 1954, the mechanism of dispersion for both turbulent flow conditions and laminar was outlined (Narasimhan, 1999). When the pollutants enter the moving fluid, advection and diffusion processes takes place at the same time. Advection is the physical movement of pollutants particles in fluid as a result of the flow. The spreading of the pollutants' fluid particles on a microscopic scale is called molecular diffusion (Fischer *et al.*, 1979; Elhadi *et al.*, 1984; Rutherford, 1994). Then the scattering of particles by the interaction between the differential advection and cross sectional diffusion is known as dispersion. Dispersion of pollutants is associated with both diffusion and velocity fluctuations caused by shear stress in open channel flows like rivers and streams (Marusic *et al.*, 2010). The inconsistency of the velocity gradient along longitudinal direction causes some solute particles with different velocity than the mean flow velocity, meaning they could be slower or faster. This leads to a continuous dispersion of solute particles within the channel cross-section through transverse and vertical processes (Robinson, 1991).

In a river or stream, at a point near where pollutants are introduced into water, the mixing and transport of solute particles normally occurs in all three directions: transverse, vertical and longitudinal. In moving away from the pollutants source, the transport of solute particles ultimately becomes a one-dimensional process (Fischer, 1967, 1968; Chatwin, 1970, 1971; Holley & Tsai, 1970). Using the principle of conservation of mass with Fick's Law of diffusion, the equation on solute concentration representing the spatial and temporal effects of advection and dispersion along longitudinal direction was derived. In a controlled volume, the equation is given by:

$$\frac{\partial(AC)}{\partial t} = -\frac{\partial(AuC)}{\partial x} + \frac{\partial}{\partial x}\left(AD_L \frac{\partial C}{\partial x}\right) \qquad (2.4)$$

where, C is the solute concentration (ML^{-3}), D_L is longitudinal dispersion co-efficient (L^2T^{-1}), u is the mean flow velocity (LT^{-1}), x is distance (L) and t is the time (T), A is the cross-sectional area of flow (L^2).

If the flow velocity is kept uniform and the channel is regular, Equation 2.4 can be simplified to the Advection Dispersion Equation (ADE) in wide use (Fischer, 1967; Fischer *et al*., 1979):

$$\frac{\partial C}{\partial t} = -u\frac{\partial C}{\partial x} + D_L\frac{\partial^2 C}{\partial x^2} \qquad (2.5)$$

The above Equation 2.5 is sometimes called the Fickian dispersion model and for it to hold the following assumption were made:

(i) velocity varies in a vertical direction only;

(ii) the fluid is regarded to be incompressible and the tracer cannot be distinguishable separated from the surrounding fluid

(iii) the tracer concentration varies along the longitudinal plane with the flow and time, the cross-section of the flow is independent of longitudinal distance and time; and

(iv) the dispersion co-efficient remains constant for a given flow.

2.5.1 Problems with ADE and Alternative Models

The ADE model has widely been used since its inception and development as a basic model to analyse solute transport in river and streams (Fischer, 1967, 68; Sooky, 1969; Chatwin, 1970; 1971; Bear, 1972; Banks, 1974; Cameron & Klute, 1977; Holley & Tsai, 1977; Fischer *et al*., 1979; Bencala & Walters, 1983; Runkel & Broshears, 1991; Runkel & Chapra, 1993; Hart, 1995; Runkel, 1998; Lees *et al*., 2000). In the last few decades other alternative models have been developed. The problems with ADE and alternative models is that during the mixing and transport of solute in river or streams, various complicated factors that influence these processes need to be considered carefully. These factors are: Geo-morphology of the streambed, channel curvature, channel side and bed irregularities, presence of dead zones and hyporheic zones. In addition there are other processes like sorption and retardation besides advection and dispersion affecting mixing and transport of solute. There is some scepticism by researchers (Day, 1975; Chatwin, 1980; Chatwin & Allen, 1985) about the credibility of the ADE model, especially in rivers where non-homogeneous turbulent mixing dominates because of the difficulty in estimation of the dispersion coefficient.

The Cells-In-Series (CIS) is one of the models that were advanced as alternative models by many researchers (Bear, 1972; Banks, 1974; Van der Molen, 1979; Beltaos, 1980; Stefan & Demetracopoulos, 1981; Beven & Young, 1988; Young & Wallis, 1993; Wang & Chen, 1996) to overcome the limitations of ADE. In this model, length of the reach is assumed to be represented by a number of thoroughly mixed cells of equal residence time. The concentration of the effluent

from a particular cell is equal to influent of the next cell, and the time is counted since injection of solute into the first cell. Banks (1974) discovered that CIS lacks some adequacy in simulating the advection component. However, it has the advantage of the governing second-order partial differential equation that can be reduced to a first-order ordinary differential equation. Beer & Young (1983) brought in a variant on the CIS model to deal with disagreement in simulating the advection part and this resulted in a new model called Aggregated Dead Zone (ADZ) model. In this model, the major physical cause of dispersion is believed to be caused by dead-zone processes in rivers. The time delay introduced allowed advection and dispersion to be de-coupled (Rutherford, 1994). The problems with model order determination of ADZ (Lees *et al.,* 2000) prompted Ghosh (2001) and Ghosh (2004) to formulate a new model known as Hybrid Cells in Series to overcome the challenges experienced by CIS and ADZ. The detail formulation of HCIS is presented in next chapter.

2.6 Common used water quality models

A selective library of water quality models like Water and Analysis Tools Model, Soil Water and Analysis Tools Model, Water Quality Analysis Simulation Program, MIKE 11, QUALs Hybrid Cells In Series and the HEC-RAS models are explored to identify some difficulties faced by water quality models. A brief literature review of each model is presented below.

2.6.1 Soil Water and Analysis Tools

Soil Water and Analysis Tools is a physical-based model that was developed by the United States Department of Agriculture in the early 1990s for the prediction of the long-term impact of rural and agricultural management practices such as irrigation, fertilisation, grazing and harvesting procedures on water (Srinivasin *et al.,* 1998). Sediment and agricultural chemicals can lead to a very complex watershed with varying soils. The Soil and Water Assessment Tool model has proven to be an effective tool for assessing water resource and nonpoint source pollution problems (Arnold *et al*., 1998; Arnold & Fohrer, 2005). However, according to Liangliang and Daoliang (2014), it has some limitations:

(i) it is difficult to manage and modify with hundreds of input files because the watershed is so large and divided into hundreds of hydrologic response units,
(ii) it does not simulate sub-daily events such as a single storm event and diurnal changes of dissolved oxygen,
(iii) it does not simulate detailed event base flood and sediment routing, and
(iv) it has difficulties in modelling floodplain erosion and snowmelt erosion

2.6.2 Water Quality Analysis Simulation Program

Water Quality Analysis Simulation Program (WASP) is a surface water quality model developed by the US Environmental Protection Agency for water quality modelling (Yang *et al*., 2007; Geza *et al.*, 2009). It is available in one, two and three dimensional dynamic models. In WASP, different interacting systems are developed comprising phosphate, nitrate, ammonia, biochemical oxygen demand, dissolved oxygen, organic nitrogen and organic phosphorus (Canu, 2004). It can be used to analyse a number of water quality problems in diverse water bodies as ponds, reservoirs, lakes, streams, rivers, coastal waters and estuaries. It can also be combined with hydrodynamic and sediment transport models that provide flows, depths, velocities, temperature, salinity and sediment fluxes. This model employs the conservation of mass and momentum equations to determine the river hydraulic characteristics. This model helps users interpret and predict water quality responses to natural phenomena and manmade pollution for various pollution management decisions. However, the model does not handle mixing zones or near field effects, sinkable or floatable materials, and it requires an extensive amount of data for calibration and verification (Liangliang & Daoliang, 2014).

2.6.3 MIKE 11

The MIKE 11 is an implicit finite difference model for one dimensional unsteady flow computation developed by the Danish Hydraulic Institute. It can be applied to looped networks and quasi-two dimensional flow simulation on floodplains. The model is capable of performing detailed modelling of rivers, including special treatment of floodplains, road overtopping, culverts, gate openings and weirs (Kamel, 2008). It is a modelling tool for computing unsteady flow, discharge and water level in rivers and channels that are based on formulation of the Saint-Venant equations. It is an advanced model that can simulate solute transport and transformation in complex river systems. However, it has its limitations. A large amount of input data is required and channel cross-sections are needed at reach boundaries, which make the calibration and evolution of the results a difficult task and requires long computational times (Cox, 2003).

2.6.4 QUALs

QUAL models such as QUAL2E, QUAL2EUNCAS, QUAL2K and QUAL2Kw were developed by US Environmental Protection Agency. These models gained a broad user base in Europe, Asia, and South and Central America (Wang *et al*., 2013). The models can simulate up to 15 parameters such as DO, BOD, temperature, algae as chlorophyll, organic nitrogen, ammonia, nitrite, nitrate, organic phosphorus, dissolved phosphorus, coliform bacteria, one arbitrary non-conservative constituent solute and three conservative constituent solutes associated with water quality in any combination chosen by the user (Riecken, 1995).

For one-dimensional steady-state models; hydrological balance, heat balance and material balance are all influenced by flow, temperature and concentration. The advective and dispersion modes of transport are considered in mass-balance that can be expressed as

$$V\frac{\partial c}{\partial t} = \frac{\partial(A_c E \partial c/\partial x)}{\partial x}dx - \frac{\partial(A_c U)}{\partial x}dx + V\frac{dc}{dt} + s \qquad (2.6)$$

where V is the volume, c is the concentration of constituent, A_c is the element cross-sectional area, E is the longitudinal dispersion coefficient, x is the distance (in the direction of flow from point load), U is the average velocity, s is the external sources of the constituent (Paliwal *et al.*, 2007). These models are suitable for dendritic river and non-point source pollution, including one-dimensional steady-state or dynamic models (Wang *et al.*, 2013). However, the sensitivity analysis showed that some of these models are highly sensitive to water depth and moderately sensitive to point source flow, carbonaceous BOD and nitrification rate (Liangliang & Daoliang, 2014).

2.6.5 Hybrid Cells In Series

Hybrid Cells In Series model was conceived to simulate advection and dispersion solute transport of conservative pollutants in rivers (Ghosh, 2001). The model demonstrated some advantages over the limitations of the Advection Dispersion Equation (ADE) model and other mixing cells–based models i.e., Aggregated Dead Done (ADZ) and the Cells in Series (CIS) models. The concentration of conservative solute in a river was estimated numerically, and the numerical solution has its own limitations. The HCIS has been further developed to include pollutant sorption process and decay process along with advection and dispersion (Kumarasamy *et al*., 2011; Kumarasamy *et al*., 2013).

2.6.6 The HEC-RAS model

The Hydrologic Engineering Centres River Analysis System model (HEC-RAS) was developed by United States Army Corps of Engineers and has been in existence for many decades. It is mostly used by water quality modellers to analyse flows and sediment transport. It employs the quickest ultimate explicit numerical scheme to solve one dimensional advection-dispersion equation. Its water quality module is capable of simulating up to ten various water quality parameters including carbonaceous BOD, dissolved oxygen, algae, organic nitrogen, dissolved inorganic phosphorus, organic phosphorus, nitrate, nitrite, ammonia and benthic algae. The disadvantage with the model is the large amount of input data required making the model difficult to calibrate (HEC-RAS, 2008).

2.7 Difficulties within Water Quality Models

The uncertainty associated with water quality models is unavoidable because no single model can accurately represent the water quality under all required model undertakings. These uncertainties primarily arise from randomness related to various model input variables, due to the water quality simulation model used and imprecision or inaccuracies (Beck, 1987; Van Straten, 1998). Despite the extensive knowledge by researchers about the processes involved in water quality simulation from laboratory experiments, applying the experimental results of models to the real environment has proven to be complicated. This is because the laboratory modelling scale is different to the actual modelling scale and the variety of species and natural environments dynamics that must be modelled (Bowie *et al.*, 1985; Chapra, 1997).

Numerous researchers have developed various water quality models for specific regions and sometimes they use certain default values of rate constants that may not be compatible to other regions (Beck, 1987; Van Straten, 1998). The water bodies of different locations are unique and hence model parameters vary widely (Lung, 1993). The data requirements increase with the complexity and application of the water quality models and also relate to the question at hand that needs to be addressed. In order for a model to be used with some degree of confidence it has to be calibrated properly. Validation of these models is crucial and sometimes requires a large set of data to be collected. The calibration assists in determining the accurate assessment of water network hydraulic conditions and changes of selected pollutants' concentration within the entire water model. The difficulties during the hydraulic calibration are real actual water flow and pressure measurement values, the appropriate setting of measurement points and assumption of allowable difference between simulated and measured values (Musz *et al*., 2009)

Water quality modelling can be very complex and difficult to execute especially with the increasing expectation of the prediction of water quality indicators with a high level of precision (Jorgensen *et al*., 1986). Viewing it from a different side, additional model complexity is expected to enhance the precision of model results, but this has proven to be unfounded in various studies (Gardner *et al.*, 1980; Van der Perk, 1997; Lees *et al*., 2000; Young *et al.*, 1996). It was found that no comprehensive model exists for all functionalities. Hence, it also pointed out that each model has its own assumptions and shortcomings (Ambrose *et al*., 2009). Some of these mentioned limitations have become a driving force for continuous research in creation of new models or upgrading the already existing ones to improve the analysis of water quality bodies. Regardless of the considerable effort and past experiences from different regional, national and worldwide projects by water quality modellers, the available water quality models are not always reliable tools for operational applications by water resource managers (Bouraoui *et al*., 2009; Hejzlar *et al.*, 2009; Kronvang *et al.*, 2009; Schoumans *et al*., 2009). In selecting a suitable model for the area under study, it is important to carefully analyse the data available for the area under investigation in order for the appropriate model to be chosen to meet its input parameters (Young *et al.*, 1996).

2.8 Summary

In the literature review presented in this chapter, it clear that an understanding of pollutants transport coupled with water quality modelling is essential in dealing with water pollution. The water quality modelling is one of the important tools, which can be used to assist water quality managers to arrive at scientific and technical making decision solutions. These models can be used to systematically produce water quality simulations over large simulated periods in a short period of time. The simulated water quality predictions can be used by decision makers and water quality managers to formulate ways that will seek to serve and curb future water pollution. Hence it will be essential to model the water quality status of the river under investigation, in order to be able to describe, understand and analyse its environmental state.

The ADE model among the water quality models presented in the literature review was widely used as a standard model at the time when there were few or no alternative models for solute transport in the streams or rivers. However, difficulties in the estimation of D_L created some problems in its application. Alternative conceptual models to the ADE model have been formulated in last few decades, including the CIS and the ADZ models, but they have their own limitations. The CIS model cannot simulate the advection component adequately whereas the selection order for ADZ model is complicated. The HCIS was conceptualized to deal with

limitations of CIS and ADZ. Considering the models presented, the two models HEC-RAS and HCIS are selected accordingly to simulate the water quality of the Umhlangane River undertaken in this study. The HEC-RAS model is chosen because of its advanced and high development in water quality simulation. The HCIS is also considered as a developing model, to be modified in order to enhance its modelling capacities, since it has shown some most promising results over other mixing cells models (CIS and ADZ) to simulate solute transport in streams.

CHAPTER THREE

METHODOLOGY

3.1 Introduction

This chapter presents the theoretical background of HEC-RAS and HCIS including the necessary parameters required to analyse and predict water quality in natural rivers. The HCIS has also been further developed by modifying it to incorporate BOD and COD. The model is then used to characterise the water quality of the river under investigation. Its flexibility in adopting reaction kinetics along with transport processes is also explored. The approach is to use water quality parameters generated by the HEC-RAS model as a benchmark, considering its advancement and development, in order to assist in investigating the HCIS‘s modelling competency. The theoretical background and formulation of the modified HCIS model is given in detail in order to explore its strength and weaknesses.

In achieving the above, it needs to be noted that in rivers and streams, oxygen is consumed due to decay of pollutants, chemical reactions and respiration by aquatic life. It is gained by rivers and streams through the re-aeration process from the atmosphere. In addition, the decay of pollutants is widely acknowledged and follows the first order reaction kinetics (Streeter & Phelps, 1944; Rinaldi *et al.,* 1979; Thomman & Muller, 1987). The majority of the pollutants that consume oxygen are from waste water, storm water runoff from farmland or streets in urban areas and failing septic systems. The amount of oxygen is expressed in its dissolved form as dissolved oxygen (DO) and is critical to aquatic live. Therefore, it is very important that amount of oxygen consumed should not be allowed to be more than the amount of oxygen produced. If permitted, the dissolved oxygen levels could decrease to the point where conditions become unfavourable for aquatic life to survive. DO levels vary with water temperature, altitude and flow. Moving water at low temperature and high altitude is capable of dissolving more oxygen than motionless water at high temperature. Hence, the accurate prediction of DO in an aquatic environment is vital in maintaining a healthy ecosystem in our rivers. Streeter & Phelps (1944) formulated an equation relating to the general relationship between the rate of biochemical oxidation of pollutants and the dissolved oxygen concentration.

3.2 Hydrologic Engineering Centers River Analysis System

The Hydrologic Engineering Centres River Analysis System (HEC-RAS) is model that was developed by the United States Army Corps of Engineers and is freely available to the public. It is largely employed by many researchers and water quality modellers around the world to analyse flows and sediment transport. It uses a modern structured system of software that has been developed for in depth analyses of various ecological water systems. It has a water-quality analysis section that aids the user in accomplishing water quality analyses of rivers. It is capable of carrying out one-dimensional hydraulic calculation for a full system of natural and fabricated channels. It uses the quickest-ultimate explicit numerical scheme to work out the one-dimensional advection-dispersion equation (HEC–RAS, 2008). This system utilises a common geometric data representation and hydraulic computation generated by a user to analyse:

(i) steady flow water surface profile computations
(ii) unsteady flow simulation
(iii) movable boundary sediment transport computations.
(iv) water quality analysis

It is capable of modelling subcritical, supercritical and mixed-flow regime water surface profiles. The model can also perform pollutants' destiny and transport estimations taking into account water temperature, arbitrary conservative and non-conservative constituents, dissolved oxygen, dissolved phosphorus, algae, dissolved nitrogen and a Carbonaceous Biological Oxygen Demand simulation. The HEC-RAS model was successfully employed (Chihhao Fan *et al.,* 2012) to assess the impact of tides on water quality and to compute re-oxygenation coefficients of the Tan-Sui River and its tributaries, where satisfactory results were obtained. Its water quality module has been formulated considering the principle of mass conservation. The model takes into account transport and reaction processes that affect water quality variables that are broken up in the water column. It solves a one advection-dispersion transport module (HEC–RAS, 2008) for each water quality constituent as shown on equation 3.1

$$\frac{\partial}{\partial t}(VC) = -\frac{\partial}{\partial x}(QC)\Delta x + \frac{\partial}{\partial x}\left(AD_x\frac{\partial C}{\partial x}\right)\Delta x + S_L + S_B + S_k \qquad (3.1)$$

where

A = cross-sectional flow area,

Q = inflow,

x = distance along channel,

t = time,

V = volume of the water quality cell (m^3),

D_x= dispersion coefficient (m^2/s),

S_L = source or sink representing direct and diffuse loading rate ($g\ m^{-3}s^{-1}$),

C = concentration of a constituent (g/m^3),

S_B= source representing boundary loading rate for upstream, downstream, and benthic interaction ($g\ m^{-3}s^{-1}$),

S_K= source or sink representing biogeochemical reaction rate ($g\ m^{-3}s^{-1}$).

Equation 3.1 is solved for each water quality cell and for each state variable. It works in such a way that it demands that if there is a source of mass at any specific location, the mass being brought in must be accounted for. Taking if further the quickest–ultimate explicit numerical scheme finally resultant in a finite-difference solution as given below

$$V^{n+1}C^{n+1} = V^nC^n + \Delta t\left\{Q_{up}C^*_{up} - Q_{dn}C^*_{up} + D_{dn}A_{dn}\frac{\partial C^*}{\partial x_{dn}} - D_{up}A_{up}\frac{\partial C^*}{\partial x_{up}}\right\} + \Delta tSS \qquad (3.2)$$

where

C_{n+1} = concentration of a constituent at present time step (g/m^3),

C_{up*} = quickest concentration of a constituent at upstream (g/m^3),

C_n = concentration of a constituent at previous time step (g/m^3),

C_{up*} = quickest derivative of a constituent at upstream (g/m^4),

D_{up}= upstream face dispersion coefficient (m^2/s),

V_n = volume of the water quality cell at previous time step (m^3),

V_{n+1} = volume of the water quality cell at present time step (m^3),

Q_{up}= upstream face flow (m^3/s),

A_{up}= upstream face cross section area (m^2),

SS = total source and sink terms of a constituent ($g/m^3/s$).

The schematic diagrams depicting an explanation of how geometric data is captured are shown in Figure 3.4 to 3.9; the parameters involved and calibration rates and constants were selected, and boundary condition requirements are shown in Figure 4.10 to 4.18

3.3 Hybrid Cells In Series

The Hybrid Cells in Series (HCIS) model (Ghosh, 2001; Ghosh *et al.,* 2004; 2008) was conceptualised to simulate conservative solute transport of pollutants in a river and appears to defeat the limitations of the aggregated dead zone (ADZ), advection dispersion equation (ADE), and the cells in series (CIS) models (Ghosh *et al.,* 2004). In comparison to other models, Stefan and Demetracopoulos (1981) discovered that the Cells in Series model do not generate skewness in concentration-time profiles normally witnessed in tracer data from rivers. It was further established that the travel time, skewness and the rate of dispersion are functions of the number of cells, creating problems in verifying these parameters independently from each other. Beer and Young (1983) emerged with another approach to modify the CIS model to deal with the disagreement in simulating advection part of pollutants that resulted in ADZ. However, the ADZ model had some challenges and shortcomings with the estimation of the model parameters (Ghosh 2001; Ghosh *et al.,* 2004; 2008).

The HCIS was chosen to be modified for this study, based on the advantages it demonstrated over some of the mixing cells based models. The model consists of a plug flow zone and two thoroughly mixed reservoirs all of unequal residence times. A single unit of this model is capable of reproducing an asymmetric pattern of concentration-time profile showing a rising limb and a falling limb (Ghosh *et al.,* 2004). This model's behaviour is identical to that of the analytical solution of the advection–dispersion equation when the size of the basic hybrid unit is more than $4D_L/u$, where D_L=longitudinal dispersion coefficient and u = mean flow velocity. The model was further developed (Kumarasamy, 2007; Kumarasamy *et al.,* 2011) to simulate adsorption – desorption in addition to advection and dispersion processes. This was to describe the process of many pollutants that are adsorbed in the streambed materials and released during pollutant transport in a stream. The HCIS model has been modified (Kumarasamy *et al.,* 2013) for decaying or non-conservative pollutant transport simulation.

3.3.1 Conceptualisation of the HCIS Model

The model comprises of a plug flow zone and two thoroughly mixed zones of unequal residence times and are shown in Figure 3.1. The initial concentration of non-conservative pollutants in each zone is assumed to be zero and the boundary concentration changes from 0 to C_R at t = 0. The fluid is substituted in a time α in the plug flow zone, and is equal to the ratio of the volume of plug flow zone to the flow rate. The residence time of the fluid in the first and second thoroughly mixed zones are denoted as $T_1$and T_2 respectively. The flow rate is Q m^3/unit time and flow is assumed to be under a steady-state condition.

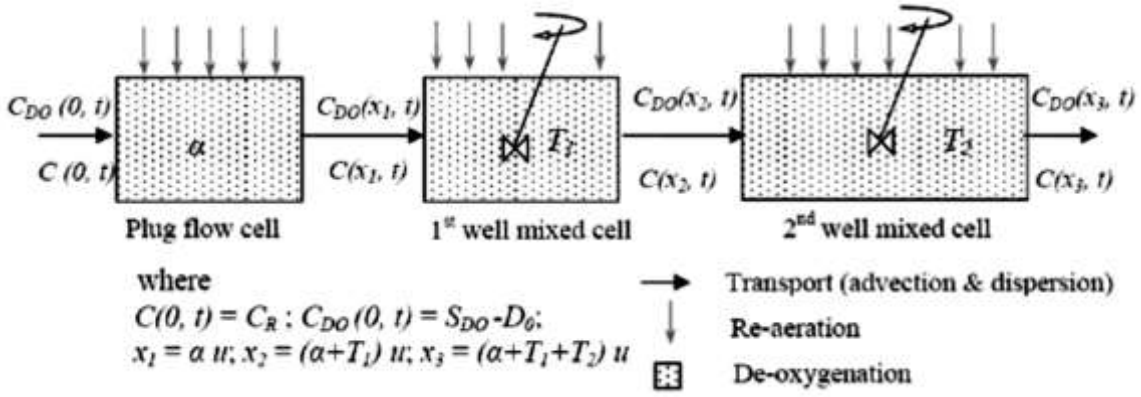

Figure 3.1 Conceptual Hybrid-Cells-in-Series Model (Kumarasamy, 2015)

Using the mass balance equation means that if the amount of material that enters a chain of processes is known, then other quantities of materials can be calculated by keeping an account of all the amount of matter in each different path. Under steady flow conditions, considering the mass-balance of dissolved oxygen and pollutants (BOD), the following equation is formulated (Kumarasamy, 2007; Kumarasamy, 2013)

$$Q\Delta t C_{DO}(x,t) - k_1 A\Delta x C(x,t)\Delta t + k_2 A\Delta x[S_{DO} - C_{DO}(x,t)]\Delta t = Q\Delta t C_{DO}(x+\Delta x, t+\Delta t) \quad (3.3)$$

Where S_{DO} = saturated DO concentration

A = cross sectional area of the flow

C(x,t) = BOD concentration

Δx = length of the hybrid cell

C_{DO} (x,t) = DO concentration

k_1= Decay rate coefficient of BOD or COD

k_2= Reaeration rate coefficient

In the current study, the mass balance equation as given in Eq 3.3, is modified to incorporate both BOD and COD to simulate DO concentration as given below in Eq 3.4

$$\begin{aligned} Q\Delta t C_{DO}(x,t) - k_1 A\Delta x C_B(x,t)\Delta t - k_1' A\Delta x C_C(x,t)\Delta t \\ + k_2 A\Delta x\left[S_{DO} - C_{DO}(x,t)\right]\Delta t = Q\Delta t C_{DO}(x+\Delta x, t+\Delta t) \end{aligned} \quad (3.4)$$

Where S_{DO} = saturated DO concentration

A = cross sectional area of the flow

C_B (x,t) = BOD concentration

C_C (x,t) = COD concentration

Δx = length of the hybrid cell

C_{DO} (x,t) = DO concentration

k_1= Decay rate coefficient of BOD

k_1' = Decay rate coefficient of BOD

k_2= Reaeration rate coefficient

Taylor series is further applied for expansion

$$Q\Delta t\left\{C_{DO}(x,t)+\frac{\partial C_{DO}(x,t)}{\partial t}\Delta t+\frac{\partial C_{DO}(x,t)}{\partial x}\Delta x+\frac{\partial}{\partial x}\left[\frac{\partial C_{DO}(x,t)}{\partial t}\Delta t\right]\Delta x\right\} \quad (3.5)$$
$$-Q\Delta t\left\{C_{DO}(x,t)\right\}=-k_1A\Delta xC_B(x,t)\Delta t-k_1'A\Delta xC_C(x,t)\Delta t+k_2A\Delta x\left[S_{DO}-C_{DO}(x,t)\right]\Delta t$$

Simplifying equation 3.5 and $Let, Q = uA$

$$\frac{\partial C_{DO}(x,t)}{\partial t}+u\frac{\partial C_{DO}(x,t)}{\partial x}=-k_1C_B(x,t)-k_1'C_C(x,t)+k_2\left[S_{DO}-C_{DO}(x,t)\right]$$

The following is the differential equation for BOD

$$\frac{\partial C(x,t)}{\partial t}+u\frac{\partial C(x,t)}{\partial x}=-k_1(x,t) \quad (3.6)$$

A similar equation can be formulated for COD replacing k_1 with k_1'

if the initial and boundary conditions for equation 3.4 and equation 3.5 are

C(x,0) = 0, x > 0;

C(0,t)= C_R, t ≥ 0

C(αu,t) = 0 0< t< α

C_{DO}(x,0) = S_{DO}, x > 0

C_{DO} (0,t) = S_{DO} – D_O, t ≥ 0

Where D_O is the boundary deficit of dissolved concentration

Then response of the plug flow zone for the given BOD becomes

$$C_B(x,t)=C_RU\left(t-\frac{x}{u}\right)exp\left(-k_1\frac{x}{u}\right) \quad (3.7)$$

C_C (x,t) can be derived similar to the above by replacing k_1 with k_1'

Substituting the following derivatives in equation 3.5

$$\frac{\partial D}{\partial t} = -\frac{\partial C_{DO}}{\partial t} and \frac{\partial D}{\partial x} = -\frac{\partial C_{DO}}{\partial x} \tag{3.8}$$

result in

$$-\left\{\frac{\partial D}{\partial t} + u\frac{\partial D}{\partial x}\right\} = -k_1 C_B - k_1^{'} C_C + k_2 D$$

Using Laplace transform

$$\frac{dD^*}{dx} = \frac{k_1}{u}\left\{C_B \frac{e^{-s\frac{x}{u}}}{s} e^{-k_1\frac{x}{u}}\right\} + \frac{k_1^{'}}{u}\left\{C_C \frac{e^{-s\frac{x}{u}}}{s} e^{-k_1^{'}\frac{x}{u}}\right\} - \left(\frac{s+k_2}{u}\right) D^* \tag{3.9}$$

Taking the inverse of Laplace transform of equation 3.9 and simplifying it. The dissolved oxygen within plug flow cell becomes

$$C_{DO}(x,t) = S_{DO} - \left\{\begin{array}{l} C_B\left(\frac{k_1}{k_2-k_1}\right)\left[e^{-\frac{k_1}{u}x} - e^{-\frac{k_2}{u}x}\right]U\left(t-\frac{x}{u}\right) \\ +C_C\left(\frac{k_1^{'}}{k_2-k_1^{'}}\right)\left[e^{-\frac{k_1^{'}}{u}x} - e^{-\frac{k_2}{u}x}\right]U\left(t-\frac{x}{u}\right) + D_0 e^{-\frac{k_2}{u}x}U\left(t-\frac{x}{u}\right) \end{array}\right\} \tag{3.10}$$

The dissolved oxygen concentration at the end of plug flow zone is

$$C_{DO}(\alpha u,t) = S_{DO} - \left\{\begin{array}{l} C_B\left(\frac{k_1}{k_2-k_1}\right)\left[e^{-k_1\alpha} - e^{-k_2\alpha}\right]U(t-\alpha) \\ +C_C\left(\frac{k_1^{'}}{k_2-k_1^{'}}\right)\left[e^{-k_1^{'}\alpha} - e^{-k_2\alpha}\right]U(t-\alpha) + D_0 e^{-k_2\alpha}U(t-\alpha) \end{array}\right\} \tag{3.11}$$

It needs to be noted that the effluent from the plug flow becomes the influent for the first thoroughly mixed zone. Similarly using the mass balance

$$\begin{aligned} V_1\,\Delta C_{DO} = & \left\{ S_{DO} - \left\{\begin{array}{l} C_B\left(\frac{k_1}{k_2-k_1}\right)\left[e^{-k_1\alpha} - e^{-k_2\alpha}\right]U(t-\alpha) \\ +C_C\left(\frac{k_1^{'}}{k_2-k_1^{'}}\right)\left[e^{-k_1^{'}\alpha} - e^{-k_2\alpha}\right]U(t-\alpha) + D_0 e^{-k_2\alpha}U(t-\alpha) \end{array}\right\} \right\} Q\Delta t \\ & - C_{DO} Q\,\Delta t - k_1 V_1\, C_B \Delta t - k_1^{'} V_1\, C_C \Delta t + k_2 V_1 (S_{DO} - C_{DO})\Delta t \end{aligned} \tag{3.12}$$

Where V_1 is the volume of the first thoroughly mixed zone

Solving above mass balance equation, the dissolved oxygen deficit at the end of first thoroughly mixed zone is solved to be

$$
\begin{aligned}
D = {} & C_B U(t-\alpha)\left(\frac{k_1}{k_2-k_1}\right)\left(\frac{1}{1+k_2T_1}\right)\left(e^{-k_1\alpha}-e^{-k_2\alpha}\right)\left[1-e^{-\left(\frac{1+k_2T_1}{T_1}\right)[t-\alpha]}\right] \\
& + C_B U(t-\alpha)e^{-k_1\alpha}\left(\frac{T_1k_1}{1+k_1T_1}\right)\frac{1}{(1+k_2T_1)}\left[1-e^{-\left(\frac{1+k_2T_1}{T_1}\right)[t-\alpha]}\right] \\
& - C_B U(t-\alpha)e^{-k_1\alpha}\left(\frac{k_1}{k_2-k_1}\right)\frac{1}{(1+k_1T_1)}\left[e^{-\left(\frac{1+k_1T_1}{T_1}\right)[t-\alpha]}-e^{-\left(\frac{1+k_2T_1}{T_1}\right)[t-\alpha]}\right] \\
& + C_C U(t-\alpha)\left(\frac{k_1'}{k_2-k_1'}\right)\left(\frac{1}{1+k_2T_1}\right)\left(e^{-k_1'\alpha}-e^{-k_2\alpha}\right)\left[1-e^{-\left(\frac{1+k_2T_1}{T_1}\right)[t-\alpha]}\right] \\
& + C_C U(t-\alpha)e^{-k_1'\alpha}\left(\frac{T_1k_1'}{1+k_1'T_1}\right)\frac{1}{(1+k_2T_1)}\left[1-e^{-\left(\frac{1+k_2T_1}{T_1}\right)[t-\alpha]}\right] \\
& - C_C U(t-\alpha)e^{-k_1'\alpha}\left(\frac{k_1'}{k_2-k_1'}\right)\frac{1}{(1+k_1'T_1)}\left[e^{-\left(\frac{1+k_1'T_1}{T_1}\right)[t-\alpha]}-e^{-\left(\frac{1+k_2T_1}{T_1}\right)[t-\alpha]}\right] \\
& + D_0 U(t-\alpha)e^{-k_2\alpha}\frac{1}{(1+k_2T_1)}\left[1-e^{-\left(\frac{1+k_2T_1}{T_1}\right)[t-\alpha]}\right]
\end{aligned}
\tag{3.13}
$$

Hence, dissolved oxygen concentration of the effluent from the first mixed zone is; $C_{DO} = S_{DO} - D$. Similarly for the second thoroughly mixed zone the effluent of the first mixed zone is the inflow to the second mixed zone and using mass balance.

$$
\begin{aligned}
V_2\Delta C_{DO} = {} & \left\{ S_{DO} - \left\{ C_B U(t-\alpha)\left(\frac{k_1}{k_2-k_1}\right)\left(\frac{1}{1+k_2T_1}\right)\left(e^{-k_1\alpha}-e^{-k_2\alpha}\right)\left[1-e^{-\left(\frac{1+k_2T_1}{T_1}\right)[t-\alpha]}\right] \right.\right. \\
& + C_B U(t-\alpha)e^{-k_1\alpha}\left(\frac{T_1k_1}{1+k_1T_1}\right)\left(\frac{1}{1+k_2T_1}\right)\left[1-e^{-\left(\frac{1+k_2T_1}{T_1}\right)[t-\alpha]}\right] \\
& - C_B U(t-\alpha)e^{-k_1\alpha}\left(\frac{k_1}{k_2-k_1}\right)\left(\frac{1}{1+k_1T_1}\right)\left[e^{-\left(\frac{1+k_1T_1}{T_1}\right)[t-\alpha]}-e^{-\left(\frac{1+k_2T_1}{T_1}\right)[t-\alpha]}\right] \\
& + C_C U(t-\alpha)\left(\frac{k_1'}{k_2-k_1'}\right)\left(\frac{1}{1+k_2T_1}\right)\left(e^{-k_1'\alpha}-e^{-k_2\alpha}\right)\left[1-e^{-\left(\frac{1+k_2T_1}{T_1}\right)[t-\alpha]}\right] \\
& + C_C U(t-\alpha)e^{-k_1'\alpha}\left(\frac{T_1k_1'}{1+k_1'T_1}\right)\left(\frac{1}{1+k_2T_1}\right)\left[1-e^{-\left(\frac{1+k_2T_1}{T_1}\right)[t-\alpha]}\right] \\
& - C_C U(t-\alpha)e^{-k_1'\alpha}\left(\frac{k_1'}{k_2-k_1'}\right)\left(\frac{1}{1+k_1'T_1}\right)\left[e^{-\left(\frac{1+k_1'T_1}{T_1}\right)[t-\alpha]}-e^{-\left(\frac{1+k_2T_1}{T_1}\right)[t-\alpha]}\right] \\
& \left.\left. + D_0 U(t-\alpha)e^{-k_2\alpha}\left(\frac{1}{1+k_2T_1}\right)\left[1-e^{-\left(\frac{1+k_2T_1}{T_1}\right)[t-\alpha]}\right]\right\} \right\} Q\Delta t \\
& - C_{DO}Q\Delta t - k_1V_2C_B\Delta t - k_1'V_2C_C\Delta t + k_2V_2(S_{DO}-C_{DO})\Delta t
\end{aligned}
\tag{3.14}
$$

where V_2 is the volume of second thoroughly mixed zone

Then the dissolved oxygen at the end of first thoroughly mixed zone is exit of first hybrid unit

$$
\begin{aligned}
D = & \left\{ \left[\begin{array}{l} C_B U(t-\alpha)\left(\frac{k_1}{k_2-k_1}\right)\left(\frac{1}{1+k_2T_1}\right)\left(e^{-k_1\alpha}-e^{-k_2\alpha}\right)+C_B U(t-\alpha)e^{-k_1\alpha}\left(\frac{T_1k_1}{1+k_1T_1}\right)\frac{1}{(1+k_2T_1)} \\ +C_C U(t-\alpha)\left(\frac{k_1^{'}}{k_2-k_1^{'}}\right)\left(\frac{1}{1+k_2T_1}\right)\left(e^{-k_1^{'}\alpha}-e^{-k_2\alpha}\right)+C_C U(t-\alpha)e^{-k_1^{'}\alpha}\left(\frac{T_1k_1^{'}}{1+k_1^{'}T_1}\right)\frac{1}{(1+k_2T_1)} \end{array} \right] \right\} \\
& \left[\frac{1}{1+k_2T_2}\left(1-e^{-\left(\frac{1+k_2T_2}{T_2}\right)[t-\alpha]}\right)-\frac{T_1}{T_1-T_2}\left(e^{-\left(\frac{1+k_2T_1}{T_1}\right)[t-\alpha]}-e^{-\left(\frac{1+k_2T_2}{T_2}\right)[t-\alpha]}\right)\right] \\
& -C_B U(t-\alpha)e^{-k_1\alpha}\left(\frac{k_1}{k_2-k_1}\right)\frac{1}{(1+k_1T_1)}\left[\frac{T_1}{\left[T_1(1+k_2T_2)-T_2(1+k_1T_1)\right]}\left(e^{-\left(\frac{1+k_1T_1}{T_1}\right)[t-\alpha]}-e^{-\left(\frac{1+k_2T_2}{T_2}\right)[t-\alpha]}\right)-\frac{T_1}{T_1-T_2}\left(e^{-\left(\frac{1+k_2T_1}{T_1}\right)[t-\alpha]}-e^{-\left(\frac{1+k_2T_2}{T_2}\right)[t-\alpha]}\right)\right] \\
& -C_C U(t-\alpha)e^{-k_1^{'}\alpha}\left(\frac{k_1^{'}}{k_2-k_1^{'}}\right)\frac{1}{(1+k_1^{'}T_1)}\left[\frac{T_1}{\left[T_1(1+k_2T_2)-T_2(1+k_1^{'}T_1)\right]}\left(e^{-\left(\frac{1+k_1^{'}T_1}{T_1}\right)[t-\alpha]}-e^{-\left(\frac{1+k_2T_2}{T_2}\right)[t-\alpha]}\right)-\frac{T_1}{T_1-T_2}\left(e^{-\left(\frac{1+k_2T_1}{T_1}\right)[t-\alpha]}-e^{-\left(\frac{1+k_2T_2}{T_2}\right)[t-\alpha]}\right)\right] \\
& +\left[C_B U(t-\alpha)e^{-k_1\alpha}\frac{k_1}{(1+k_1T_1)}\frac{1}{(1+k_1T_2)}\left(\frac{T_2}{1+k_2T_2}\left(1-e^{-\left(\frac{1+k_2T_2}{T_2}\right)[t-\alpha]}\right)-\frac{1}{k_2-k_1}\left(e^{-\left(\frac{1+k_1T_2}{T_2}\right)[t-\alpha]}-e^{-\left(\frac{1+k_2T_2}{T_2}\right)[t-\alpha]}\right)\right)\right] \\
& -\left[C_B U(t-\alpha)e^{-k_1\alpha}\frac{k_1}{(1+k_1T_1)}\frac{T_1}{(T_1-T_2)}\left(\frac{T_1T_2}{\left[T_1(1+k_2T_2)-T_2(1+k_1T_1)\right]}\left(e^{-\left(\frac{1+k_1T_1}{T_1}\right)[t-\alpha]}-e^{-\left(\frac{1+k_2T_2}{T_2}\right)[t-\alpha]}\right)-\frac{1}{k_2-k_1}\left(e^{-\left(\frac{1+k_1T_2}{T_2}\right)[t-\alpha]}-e^{-\left(\frac{1+k_2T_2}{T_2}\right)[t-\alpha]}\right)\right)\right] \\
& +\left[C_C U(t-\alpha)e^{-k_1^{'}\alpha}\frac{k_1^{'}}{(1+k_1^{'}T_1)}\frac{1}{(1+k_1^{'}T_2)}\left(\frac{T_2}{1+k_2T_2}\left(1-e^{-\left(\frac{1+k_2T_2}{T_2}\right)[t-\alpha]}\right)-\frac{1}{k_2-k_1^{'}}\left(e^{-\left(\frac{1+k_1^{'}T_2}{T_2}\right)[t-\alpha]}-e^{-\left(\frac{1+k_2T_2}{T_2}\right)[t-\alpha]}\right)\right)\right] \\
& -\left[C_C U(t-\alpha)e^{-k_1^{'}\alpha}\frac{k_1^{'}}{(1+k_1^{'}T_1)}\frac{T_1}{(T_1-T_2)}\left(\frac{T_1T_2}{\left[T_1(1+k_2T_2)-T_2(1+k_1^{'}T_1)\right]}\left(e^{-\left(\frac{1+k_1^{'}T_1}{T_1}\right)[t-\alpha]}-e^{-\left(\frac{1+k_2T_2}{T_2}\right)[t-\alpha]}\right)-\frac{1}{k_2-k_1^{'}}\left(e^{-\left(\frac{1+k_1^{'}T_2}{T_2}\right)[t-\alpha]}-e^{-\left(\frac{1+k_2T_2}{T_2}\right)[t-\alpha]}\right)\right)\right] \\
& +D_0U(t-\alpha)e^{-k_2\alpha}\frac{1}{(1+k_2T_1)}\left[\frac{1}{1+k_2T_2}\left(1-e^{-\left(\frac{1+k_2T_2}{T_2}\right)[t-\alpha]}\right)-\frac{T_1}{T_1-T_2}\left(e^{-\left(\frac{1+k_2T_1}{T_1}\right)[t-\alpha]}-e^{-\left(\frac{1+k_2T_2}{T_2}\right)[t-\alpha]}\right)\right]
\end{aligned}
$$

(3.15)

Hence, dissolved oxygen concentration of the effluent at the end of the second mixed zone is

$C_{DO} = S_{DO} - D$ (3.16)

3.3.2 Convolution technique for spatial variation of pollutants

The convolution technique is applied for the dissolved oxygen of second and subsequent hybrid units. Equation 3.16 gives a C-t profile at the end of one Hybrid unit that is at a distance Δx (unit size) from a point of pollutant injection. In order to simulate pollutant concentrations along the river reach, the convolution technique can be adopted using discrete kernel approach as follows.

$$D(n,t) = \int_0^t C[n-1),\tau]k_D(t-\tau)d\tau \quad (3.17)$$

Where C(n-1) is the concentration of pollutant at the end of (n-1)th cell and K_D is the impulse deficit of DO

This is performed by numerical integral as

$$\overline{C}(n-1,\tau) = \frac{C[(n-1),(\gamma-1)\Delta t] + C[(n-1),\gamma\Delta t]}{2}$$

$$\delta_D(M,\Delta t) = k_D(m\Delta t) - k_D(m-1)\Delta t) \quad (3.18)$$

$$D(n,t) = \sum_{\gamma=1}^{m}\left[\overline{C}(n-1),\gamma\Delta t\right)\delta_D\,(m-\gamma+1,\Delta t) \quad (3.19)$$

Where δ is discrete kernal

3.3.3 Estimation of the HCIS model parameters

The HCIS model parameters have to be estimated using Equation 3.20 to 3.23, to simulate pollutant transport. If u (mean flow velocity) and D_L (longitudinal dispersion coefficient) are known then

$\alpha = \frac{0.04\Delta x^2}{D_L}$ residence time in the plug flow zone (3.20)

$T_1 = \frac{0.05\Delta x^2}{D_L}$ residence time first thoroughly mixed zones (3.21)

$T_2 = \frac{\Delta x}{u} - \frac{0.09\Delta x^2}{D_L}$ residence time second thoroughly mixed zones (3.22)

$P_e = \frac{\Delta x u}{D_L} \geq 4$ Peclet number (3.23)

The Peclet number is related to the dispersion process and is taken as a reference index to interrelate with other parameters of the model. In order to produce advective-dispersive C-t profile it was suggested (Ghosh, 2001; Ghosh, *et al.*, 2004) that Peclet number must be greater than or equal 4.

3.3.4 Reaeration Rate and Dispersion Coefficient

As dissolved oxygen is depleted due to the consumption of oxygen by biodegradable pollutants, reaeration will be taking place at same time at a specific rate depending on the dissolved oxygen deficit. This rate is known as the re-aeration rate and is affected by the velocity, depth, temperature, internal mixing, wind mixing, surface films and many more physical properties of water (Thomann & Mueller, 1987). The coefficient (Kr) in modelling is highly sensitive and very important in predicting other water quality parameters (Bowie *et al*., 1985). There are many semi-empirical equations that can used to calculate the re-aeration coefficient. One of them is where the re-aeration coefficient is taken to be a function of temperature and hydraulic parameters, that is depth and velocity

$$k_{20} = 2.148\, v^{0.878}\, H^{-1.48} \quad (3.24)$$

where k_{20} is the re-aeration coefficient rate at 20 degree Celsius

v is the average flow velocity (m/s)

H is the average depth of flow in the river (m)

The temperature effect is corrected by using the following equation

$$K_r = k_{20}\theta^{(T-20)} \quad (3.25)$$

where T is the actual temperature in the stream

θ is a constant

θ was recommended to be between 1.005 and 1.030 depending on the mixing conditions of the river (Holley, 1975; Zison *et al*., 1978). However, the most commonly employed value in practice is 1.024 (Haider *et al*., 2013).

Estimation of the longitudinal dispersion coefficient received considerable attention over the past decades by many water quality researchers (Fischer *et al*., 1979; Liu, 1977; Seo & Cheong, 1998; Kashefipour & Falconer, 2002) as a representative of the intensity of the mixing in rivers (Deng *et al*., 2001). In rivers, a number of variables have an effect on the estimation of the longitudinal dispersion coefficient. The most essential ones are: the viscosity, channel width, flow depth, density, shear velocity, mean velocity, bed slope, horizontal stream curvature, bed shape factor and bed roughness (Seo & Cheong, 1998).

Table 3.1 show some of the empirical equations formulated by various researchers to predict the dispersion coefficient.

Table 3.1 Empirical equations for predicting D_L

	Author	Equation
1	Elder (1959)	$D_L = 5.93U_*H$
2	Fisher (1967)	$D_L = 0.011\left\{\frac{u^2W^2}{HU_*}\right\}$
3	Sumer (1969)	$D_L = 6.23U_*H$
4	McQuivey & Keefer (1974)	$D_L = 0.58\left\{\frac{H}{U_*}\right\}^2 uW$
5	Liu (1977)	$D_L = 0.18\left\{\frac{u}{U_*}\right\}^{0.5}\left\{\frac{W}{H}\right\}^2 HU_*$
6	Iwasa & Aya (1991)	$D_L = 2\left\{\frac{W}{H}\right\}^{1.5} HU_*$
7	Koussis & Rodriguez-Mirasol (1998)	$D_L = 0.6\left\{\frac{W}{H}\right\}^2 HU_*$
8	Seo & Cheong (1998)	$D_L = 5.915\left\{\frac{W}{H}\right\}^{0.628}\left\{\frac{u}{U_*}\right\}^{1.428} U_*H$
9	Deng *et al* (2001)	$D_L = 5.915\frac{0.15}{8\varepsilon_{t0}}\left\{\frac{W}{H}\right\}^{5/3}\left\{\frac{u}{U_*}\right\}^2 for\ \frac{W}{H} > 10$ where $\varepsilon_{t0} = 0.145 + \frac{1}{3520}\left\{\frac{u}{U_*}\right\}\left\{\frac{W}{H}\right\}^{1.38}$
10	Kashefipour & Falconer (2002)	$D_L = 2\left\{\frac{u}{U_*}\right\}^{0.96}\left\{\frac{W}{H}\right\}^{1.25} U_*H$
11	Sahay & Dutta (2009)	$D_L = 10.612\left\{\frac{u}{U_*}\right\}Hu$

where, $U_* = \sqrt{gHs}$; u = the flow velocity, W = width, H = depth, U_* = shear velocity and s = slope

The challenge with the existing dispersion equations models is about their prediction accuracy of the dispersion coefficient. Hence, Etemad-Shahidi and Taghipour (2012) formulated a new dispersion equation with the assistance of the latest M5 algorithm. The M5 algorithm was employed because of its capability to create simpler trees that can sufficiently deal with enumerated and missing values (Wang & Witten, 1997). The investigation by Etemad-Shahidi and Taghipour (2012) resulted in Model Tree (MT) dispersion equations 3.26 and 3.27

$$\text{if } \frac{W}{H} \leq 30.6 \ \ then\ D_L = 15.49 \left\{\frac{W}{H}\right\}^{0.78} \left\{\frac{u}{U_*}\right\}^{0.11} HU_* \quad 3.26$$

$$\text{if } \frac{W}{H} \geq 30.6\ then\ D_L = 14.12 \left\{\frac{W}{H}\right\}^{0.61} \left\{\frac{u}{U_*}\right\}^{0.85} HU_* \quad 3.27$$

The splitting parameter is $\frac{W}{H}$ (30.6), and was introduced to minimise the prediction error and do not necessarily have a physical interpretation (Bhattacharya *et al*., 2007; Bonakdar & Etemad-Shahidi 2011). Etemad-Shahidi and Taghipour (2012) dispersion equation outperformed the Liu (1977), Seo and Cheong (1998), Deng *et al* (2001), and Sahay and Dutta (2009) dispersion equations in terms of accuracy. The MT dispersion equation had and accuracy of 63 %, the highest among the five equations. The second best nearest value of the accuracy to that of MT is that of Liu (1977) with 51% (Etemad-Shahidi & Taghipour, 2012).

Etemad-Shahidi and Taghipour (2012) also found Liu (1977), Seo and Cheong (1998), Deng *et al* (2001), and Sahay and Dutta (2009) to be over predicting the dispersion coefficient by 1.7 times more than the under predicted instances. The over prediction of the longitudinal dispersion coefficient have a possibility of obtaining lower maximum concentration (Etemad-Shahidi & Taghipour, 2012). The MT dispersion equation will be used in this study to estimate the dispersion coefficient for Umhlangane River since it was demonstrated to be more accurate than other models (Etemad-Shahidi & Taghipour, 2012).

The flow chart in Figure 3.2 represents the general process that of the new modified HCIS undertakes which was programmed into a FORTRAN. The numerous variable inputs of the model i.e. m and n implies that the number of observations and the time steps or even the hybrid units may change from reach to reach as in the case of the Umhlangane river.

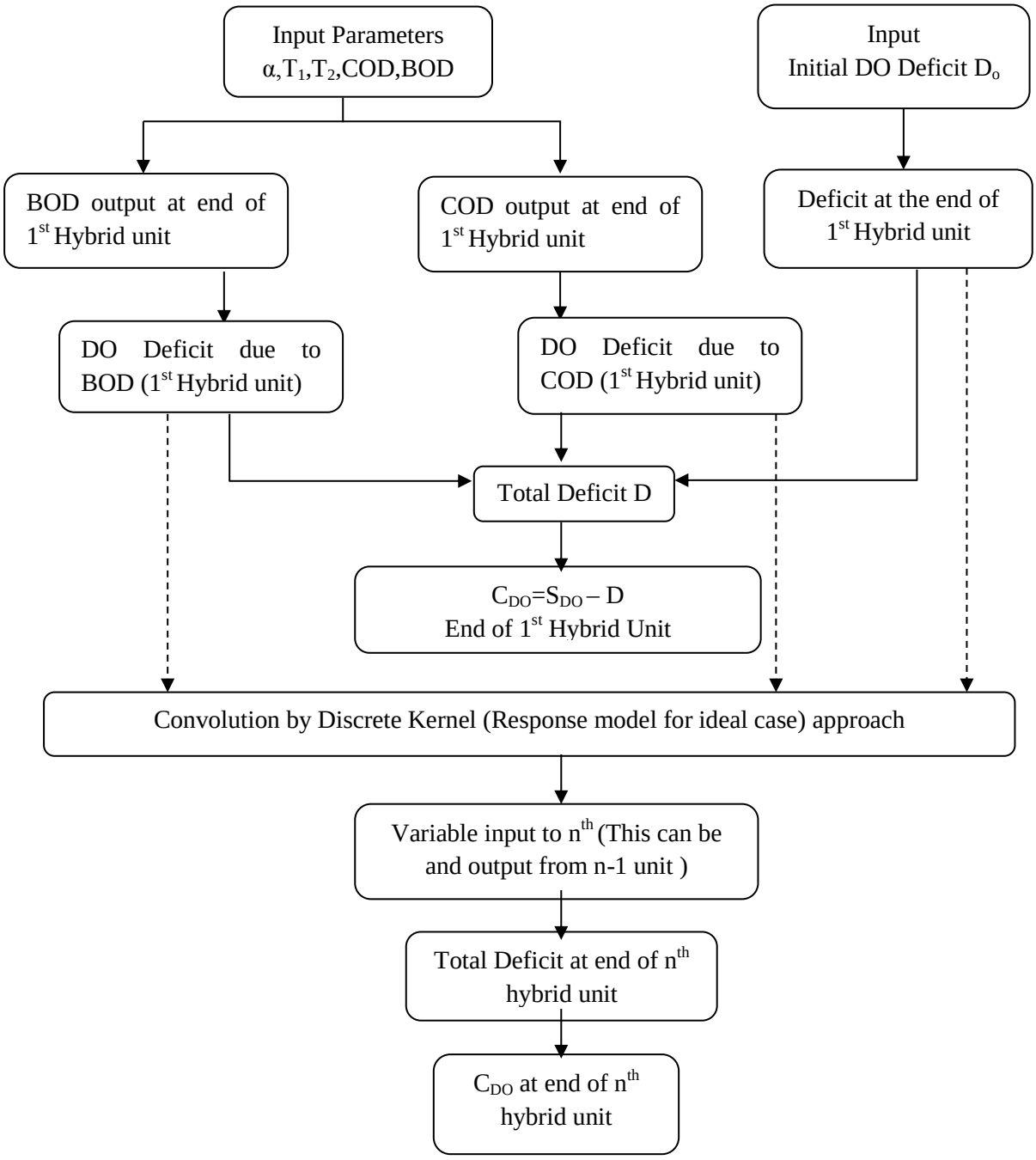

Figure 3.2 Flow chart representing the process programmed into FORTRAN

3.4 HECRAS - Model Parameters

3.4.1 Geometric data

Firstly a river profile (i.e. depth, width, length, elevation and any variation in river flow channels of the entire river) were determined. Cross sectional data entered into geometric tables to capture changes in area conveyance with respect to elevation. Another crucial element that needed to be carefully determined was the hydraulic conditions because of the influence they have on water quality. The schematic diagram in Figure 3.3 shows how the various river reaches are considered. The river system schematic is prepared by drawing and joining the various reaches of the system within the geometric data editor. Each river reach on the schematic is given a unique identifier and their junctions are numbered in numerical order down the river. The 17.3 km river shown was divided into the same reaches as the HCIS model.

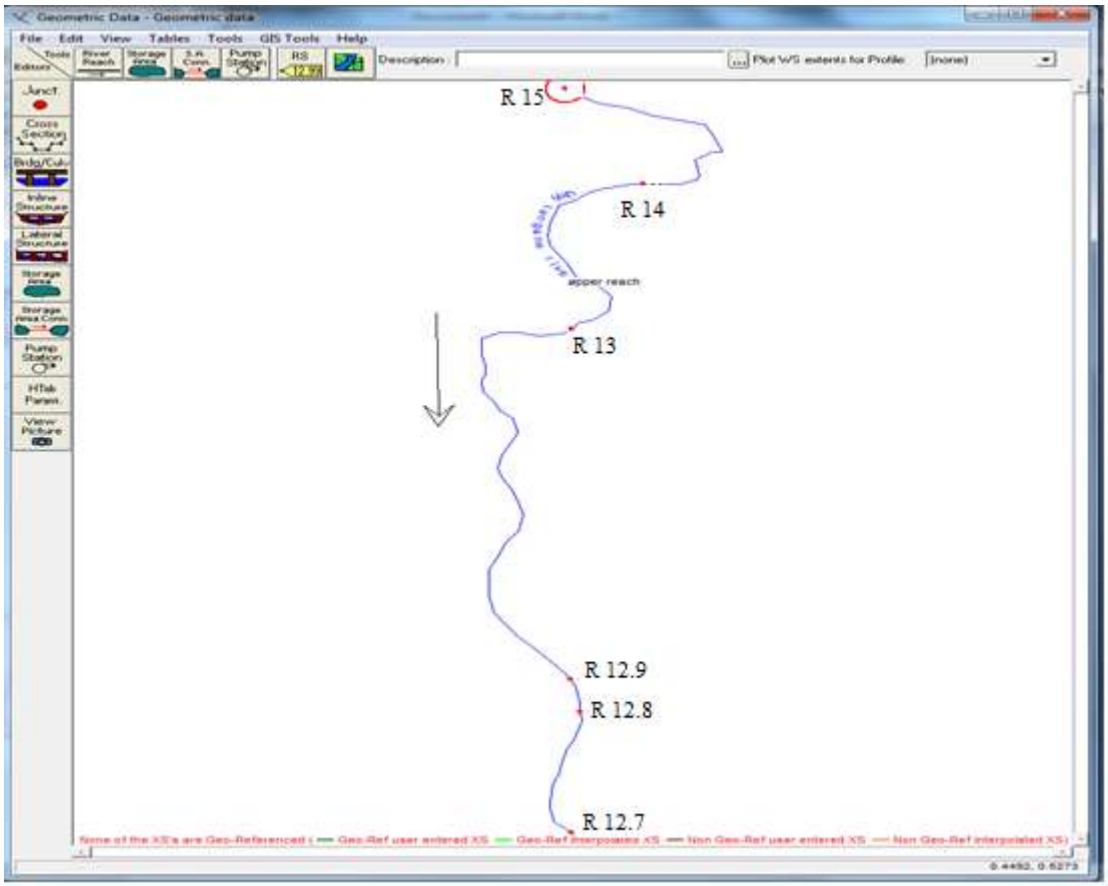

Figure .3.3 Geometric profile of Umhlangane River

3.4.2 Channel characteristics:

In accordance with the channel geometry and profile, the river was divided into six hydraulic reaches with Manning's equation inputs i.e. channel slope, bottom width and roughness coefficient. The average channel slope was calculated for each hydraulic reach for HEC-RAS output from google earth.

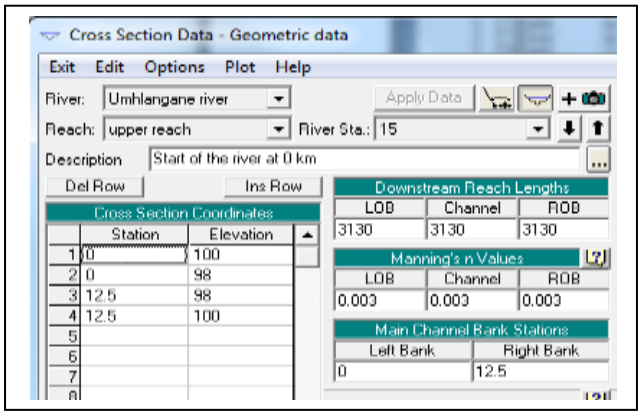

Figure 3.4 River station 15

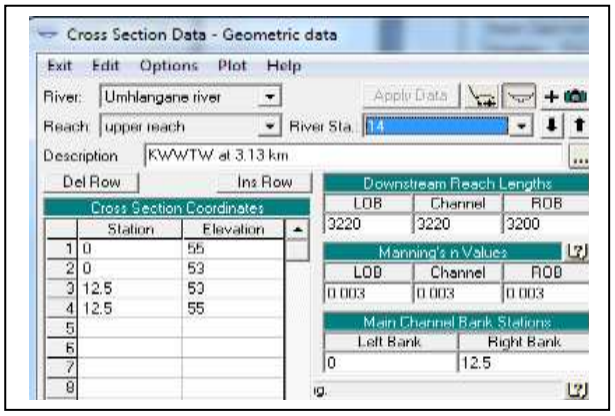

Figure 3.5 River station 14

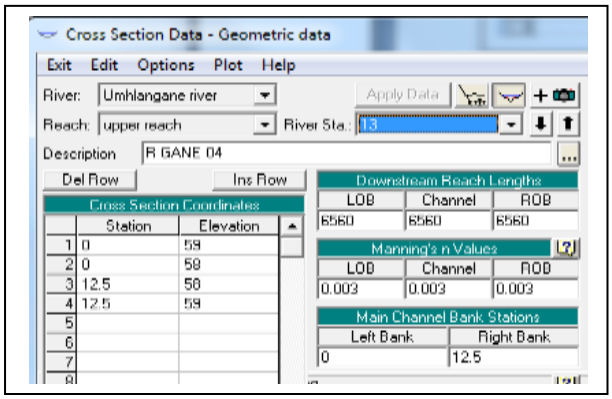

Figure 3.6 River station 13

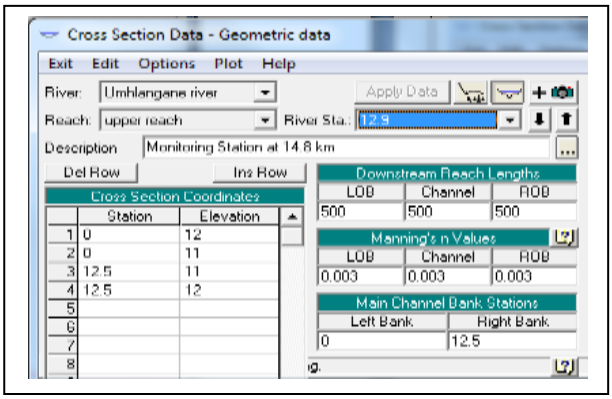

Figure 3.7 River station 12.9

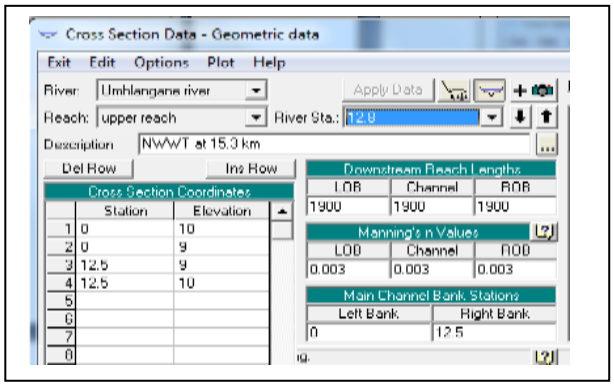

Figure 3.8 River station 12.8

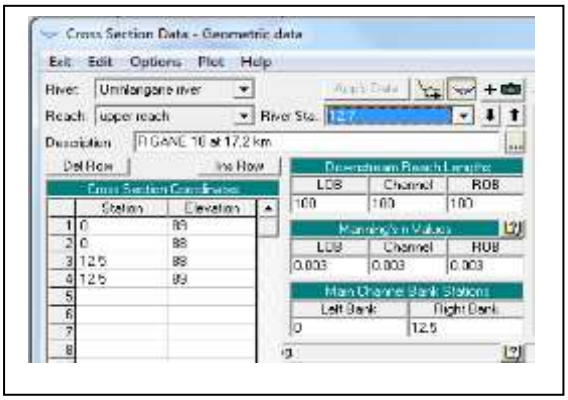

Figure 3.9 River station 12.7

3.5 Summary

To model the water quality of Umhlangane River it is important and necessary to apply the selected water quality models correctly to properly represent the current state of the river. In this chapter the HCIS and HEC-RAS modelling execution procedures were exhibited in detail. These include each model's input parameter requirements and the geometric profile of the river. The models' input parameters are significant because they interrelate directly with their outputs. The greater the number of model parameters required; the greater the number of computational runs that will be needed to produce the output simulation response.

The HCIS model, as shown earlier, is derived and established using the basic principle of conservation of mass to estimate the dissolved oxygen concentration. The pure advection in the HCIS model is expressed by an explicitly derived time parameter and, in addition, it represents the advection and dispersion components implicitly with two time parameters. Since HCIS is flexibly able to adopt reaction kinetics along with transport processes, the new modules for the HCIS are developed to simulate other water quality parameters. The new HCIS model was developed and modified by incorporating biochemical oxygen demand and chemical oxygen demand into the mass balance equation. The new equation arrangement was then programmed into FORTRAN for water quality simulation.

The HEC-RAS model is advanced, well developed and capable of simulating many more water quality parameters. These parameters are water temperature, arbitrary conservative and non-conservative constituents, dissolved oxygen, dissolved phosphorus, algae, dissolved nitrogen and carbonaceous biological oxygen demand simulation. In this model, one advection-dispersion transport module is solved for each water quality constituent, and this seems to increase its accuracy. The simulation results of HEC-RAS in this study will be utilised as a benchmark in evaluating the modelling abilities of the newly modified HCIS model because of it's high and advanced water quality development.

CHAPTER FOUR
STUDY AREA AND DATA ANALYSIS

4.1 Introduction

This chapter presents the description of the study area, location of data sampling points and the preparation for the HEC-RAS and HCIS models. The data was collected and analysed by Ethekweni Water Services in their Labs. The provided data is analysed further to ascertain the various input requirements of the modelling work to be performed. The important or influential parameters such as BOD, COD, DO, decay rates re-aeration dispersion coefficient were analysed to evaluate the then current state of the river and to minimise uncertainties. The two models, the HEC-RAS and the HCIS models, were set up to investigate a study area (Umhlangane River). They are then subjected to the parameters estimation. The values of parameters that were perceived to be the most important and associated with the simulation of water quality in each reach for the HEC-RAS model and HCIS models were identified. These included BOD and COD decay rates, reaeration rates, the Peclet number, hybrid unit sizes, reach lengths and dispersion coefficients. These are the parameters that finally determine the behavioural response and performance of the models. For water quality simulation in the HEC-RAS model and accurate determination of geometric river profile and hydraulic conditions was required. Various stations were introduced along the entire river length in such way that they created identical reaches as in the HCIS model. The observed data (Appendix A) at KwaMashu Waste Treatment Works sampling point are used as the upstream boundary conditions at reach R15 as shown in Figure 3.3.

4.2 Study Area

In this study, the Umhlangane River is selected for study due to its poor water quality (Ethekweni, 2015b). The city of Durban is confronted with the difficulties of dealing with the developmental challenges of the Umhlangane catchment. The catchment is characterised by a poorly working river system together with high levels of environmental degradation. The fast growing population and urban planning developments provided the underlying base for economic progress and public modernisation. Unfortunately this progress resulted in environmental loadings and, in this area, created serious water pollution problems for Umhlangane River shown in Figure 4.1. It has a sub catchment area of 12240ha and is located in a relatively flat coastal plain upstream of the uMgeni estuary, to the north of the uMgeni river. It is a wide and large self-collected funnel sub-catchment with a flat topography that flows off from Mt. Edgecombe, Phoenix and Inanda in north through KwaMashu and Newlands in central areas to the Springfield Flats in south.

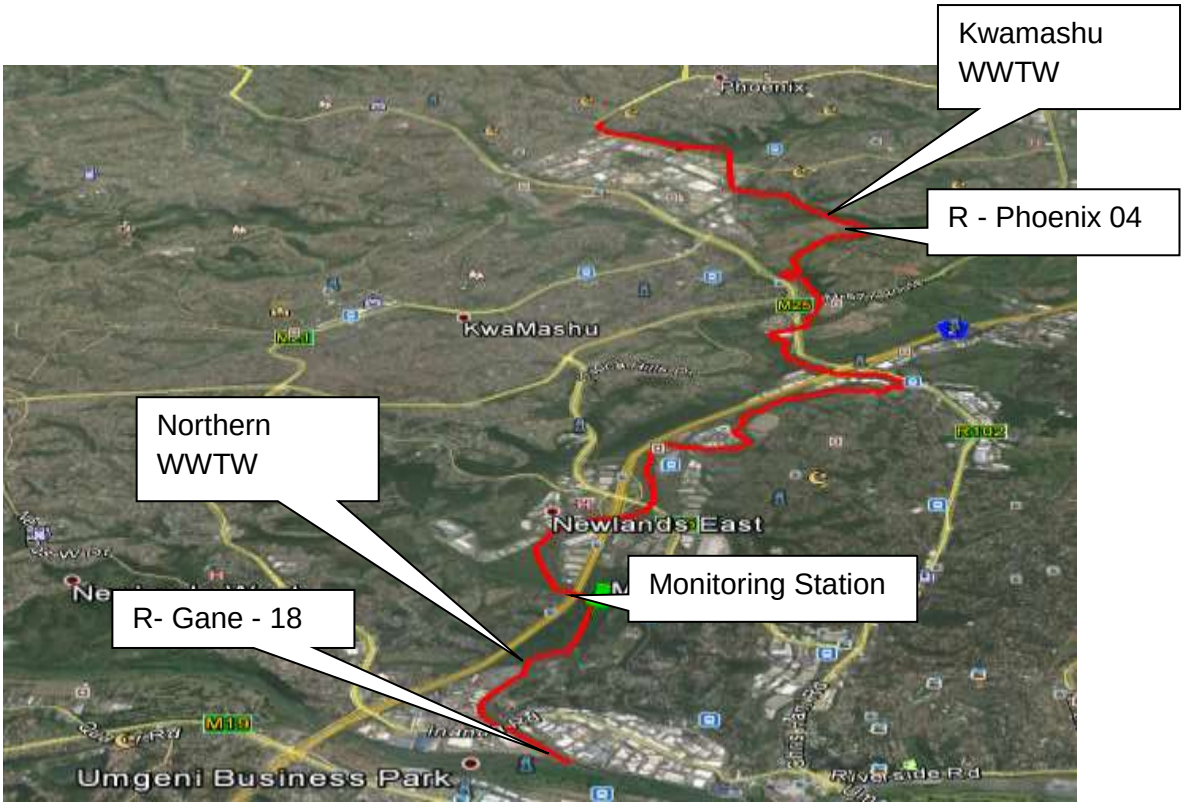

Figure 4.1 Google earth image of Umhlangane River and various data collection points

The river is encircled by areas with industrial activities especially from Phoenix, Avoca, Effingham and a portion of the Springfield flats. There are also commercial areas in KwaMashu Town Centre, Inanda MR93, Phoenix, Mt. Edgecombe and various institutional areas. About 65% of the sub-catchment is urban development, 21% is undeveloped or open space and 13% is agricultural activities in this study. Nearly 39% of the resident population do not have flush or chemical toilets, forcing them to resort to other alternatives methods such as the use of pit latrines (Ethekweni Municipality, 2015c).

4.2.1 Data Sampling points

The study uses the observed water quality data supplied by Ethekweni Water Services. The data was collected and analysed by Ethekweni Water Services technicians in their own Chemical and Microbiology laboratory (T0372) based in Pinetown. The testing laboratory facility is accredited by South African National Accreditation Service (SANAS) in accordance with recognised International Standard ISO/IEC 17025:2005 (refer to Annexure A for standards used). The samples collected for analysis were taken at Kwamashu Waste Treatment Works, R GANE 04, Monitoring Station, Northern Waste Treatment Works and R GANE 18. The locations of the sampling points where water quality data was collected are shown Figure 4.1 and their individual coordinates are tabulated in Table 4.1. In addition the average flow velocity, depth and width of this river was found to be 0.152 m/s, 1.5 m and 7.8 m respectively.

Table 4.2 Description of sampling points

Sample Point	Sample Site description	Deg. South	Deg. East
KWWTW	Kwamashu Waste Treatment Works	29 43 37.10	31 00 35.94
R GANE 04	Below Kwamashu Waste Treatment Works	29 43 39.37	30 00 43.26
MST	Monitoring Station	29 47 16.00	30 59 55.21
NWWTW	Northern Waste Treatment Works	29 47 47.39	30 59 45.12
R GANE 18	Below Northern Waste Treatment Works	29 48 23.35	30 59 43.29

The summarised water quality parameters such as BOD, COD and DO observed over a period of twelve months are shown in Figures 4.2, 4.3 and 4.4. They vary temporally from location to location based on the pollution event or source. The only set of dissolved oxygen was recorded at the monitoring station (MST) shown in Figure 4.1 and this is regarded as an important indicator in assessing water quality. The observed sets of data collected are discrete and sparse, creating difficulties in performing good quality water analyses. Despite these challenges an effort has to be made to come up with a reasonable analysis that will assist decision makers with management of the Umhlangane River and help to prevent further unnecessary water quality deterioration of this particular river.

Since no BOD values were recorded, equation 4.1 below is used to calculate BOD.

$$\text{BOD concentration} = 0.5 * \text{COD concentration} \quad (4.1)$$

Authors such as Kiepper (2010), Metcalf & Eddy (2003) and Samudro & Mankoedihardjo (2010) found this ratio to be valuable. Other authors like Rene & Saidutta (2008) and Marais & Ekama (1976) do not agree and say that the type of pollutant source and the type of the total pollutants have a significant role in the BOD to COD behaviour.

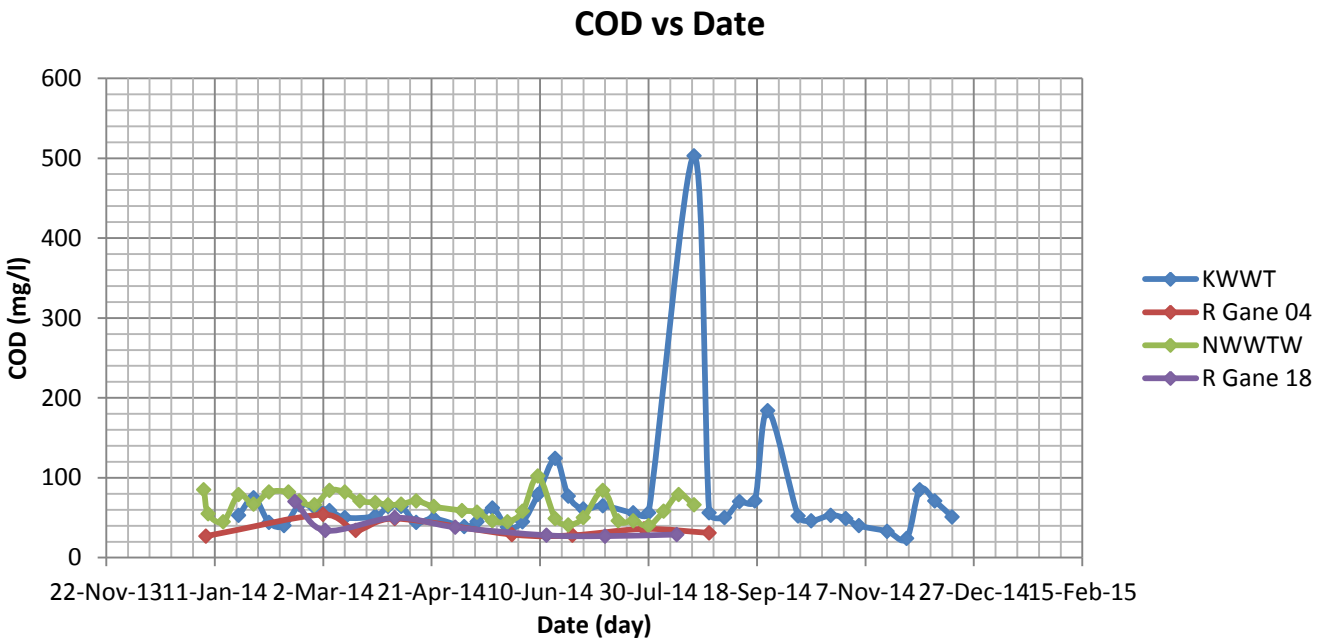

Figure 4.2 Variation of COD concentrations along Umhlangane River at various sampling points

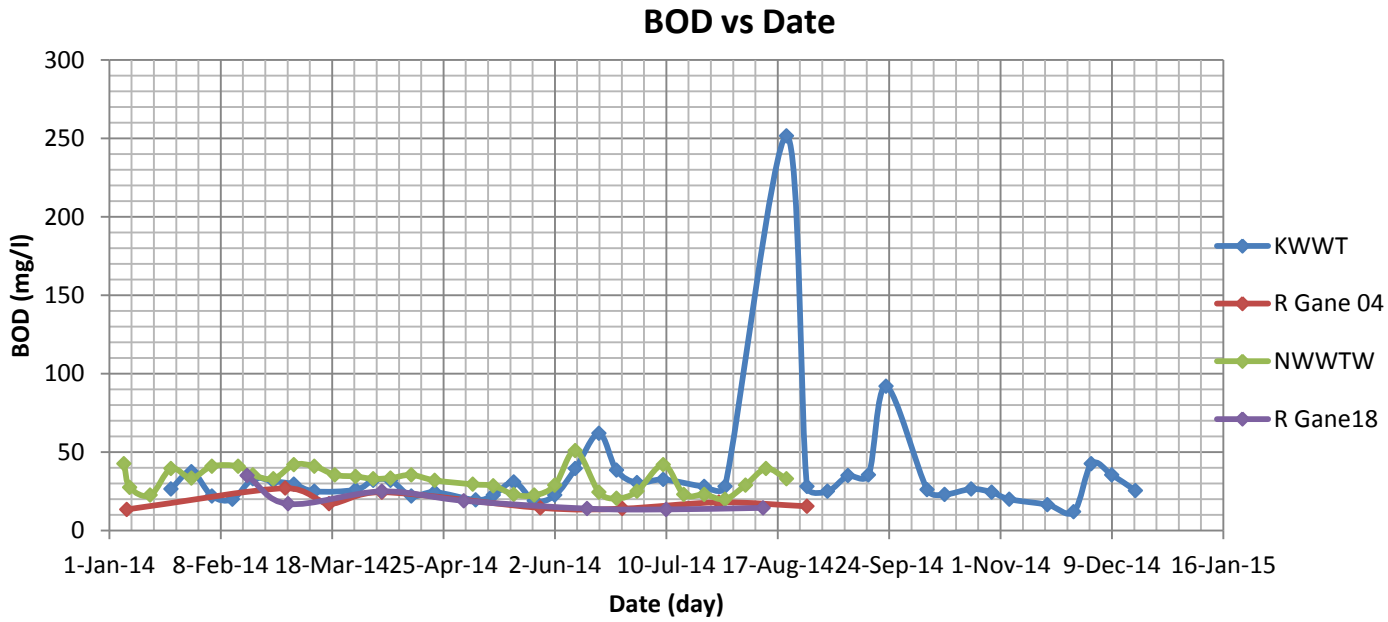

Figure 4.3 Variation of BOD concentrations along Umhlangane River at various sampling points

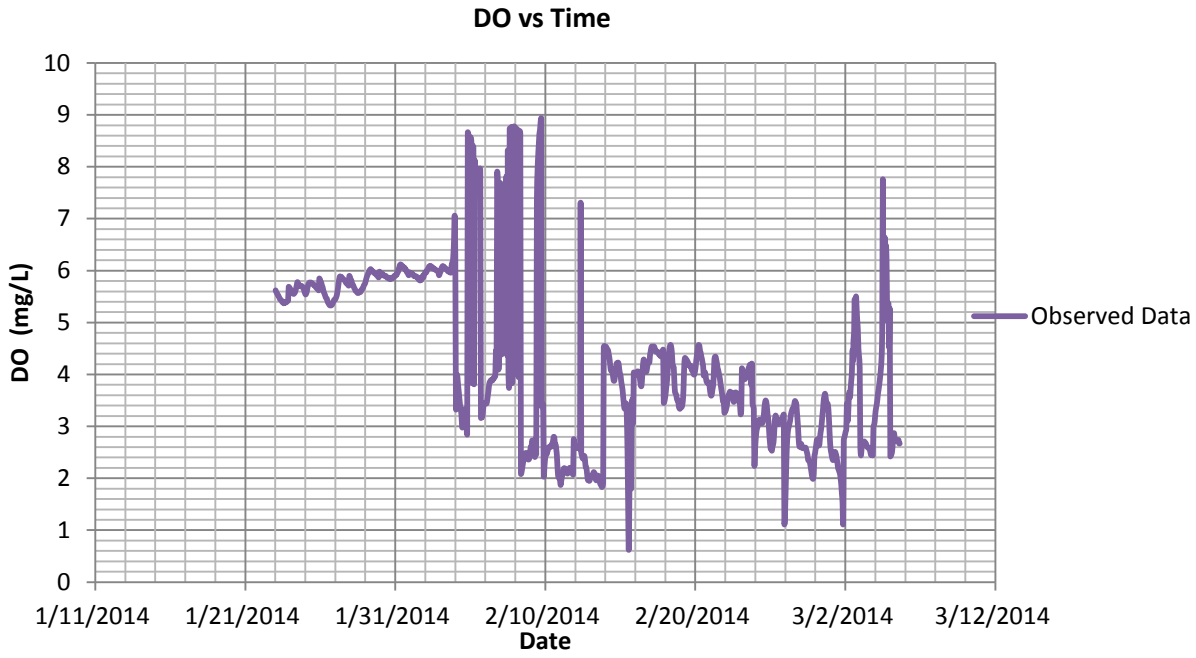

Figure 4.4 Variation of DO concentrations at the monitoring station

4.3 Reaeration Rate and Dispersion Coefficient

The reaeration rate and dispersion coefficient have been estimated using equation 3.24, 3.25, 3.26 and 3.27 respectively. For the Umhlangane River the average velocity is 0.1521 m/s and depth is 1.5 m.

Therefore k_{20}= 2.148*$0.1521^{0.878}1.5^{-1.48}$ = 0.2256 per day

with temperature correction

K_r= 0.2256* $1.024^{(19.7\ -20)}$ = 0.22 per day

and for dispersion coefficient

$U_* = \sqrt{gHs} = \sqrt{9.81 \times 1.5 \times 8.79 \times 10^{-5}}$ = 0.036 m/s

Since $\left\{\frac{7.8}{1.5}\right\} < 30.6$ then

$$D_L = 15.49\left\{\frac{7.8}{1.5}\right\}^{0.78}\left\{\frac{0.152}{0.036}\right\}^{0.11} 1.5 \times 0.036 = 3.543\text{m}^2/\text{s} = 212.58\ \text{m}^2/\text{min}$$

4.4 HEC-RAS – Calibration and Boundary conditions

4.4.1 Calibration rates and constants

The full set of calibration values that were adopted to calibrate the model are shown in Figure 4.5

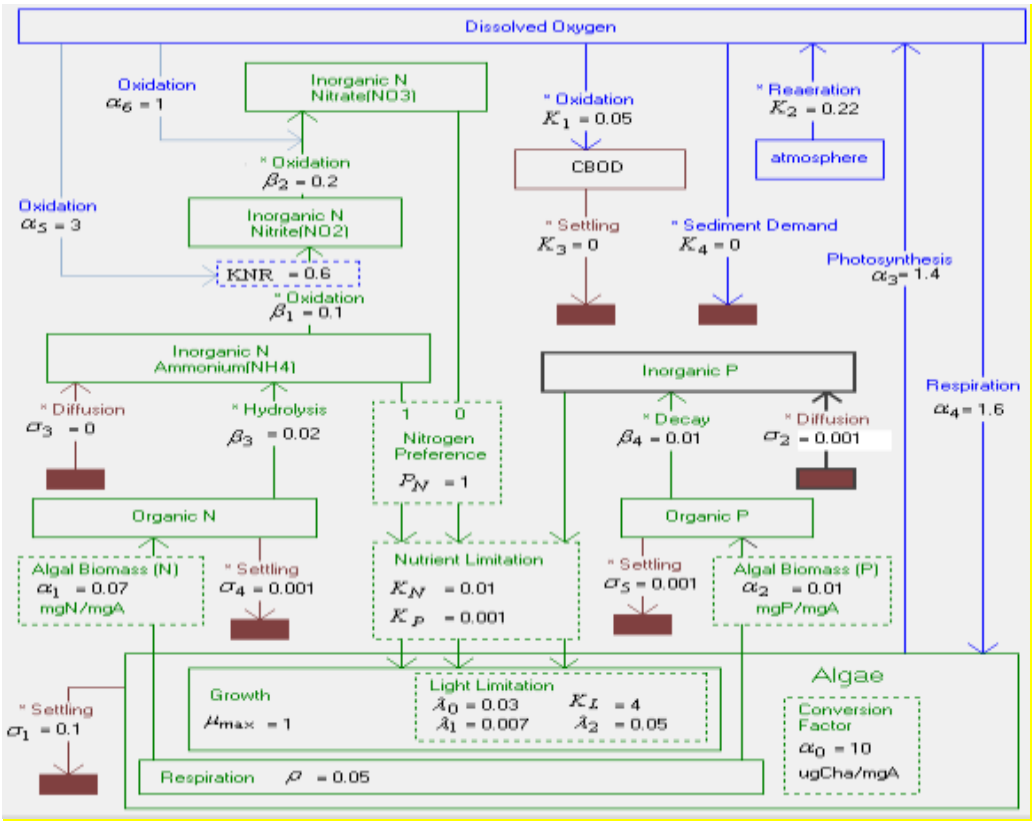

Figure 4.5 Calibration Parameters constants (HEC – RAS, 2008)

4.4.2 Boundary conditions

The boundary conditions are very important as they assist in specifying the starting points of the parameters to be modelled and to generate time series. Figure 4.6 depicts how data of the boundary conditions of the BOD in the left column is entered for different reaches and what the data profile entered looks like on a graph in the right hand side column. In the same way the rest of the boundary conditions in the left column are entered, using observed data extracted from Appendix A to C. BOD and COD were generated in time steps of pollutants concentration per day from 22 Jan 2014 to 19 Jan 2015 and DO for every 30 minutes only for R13 to R12.9

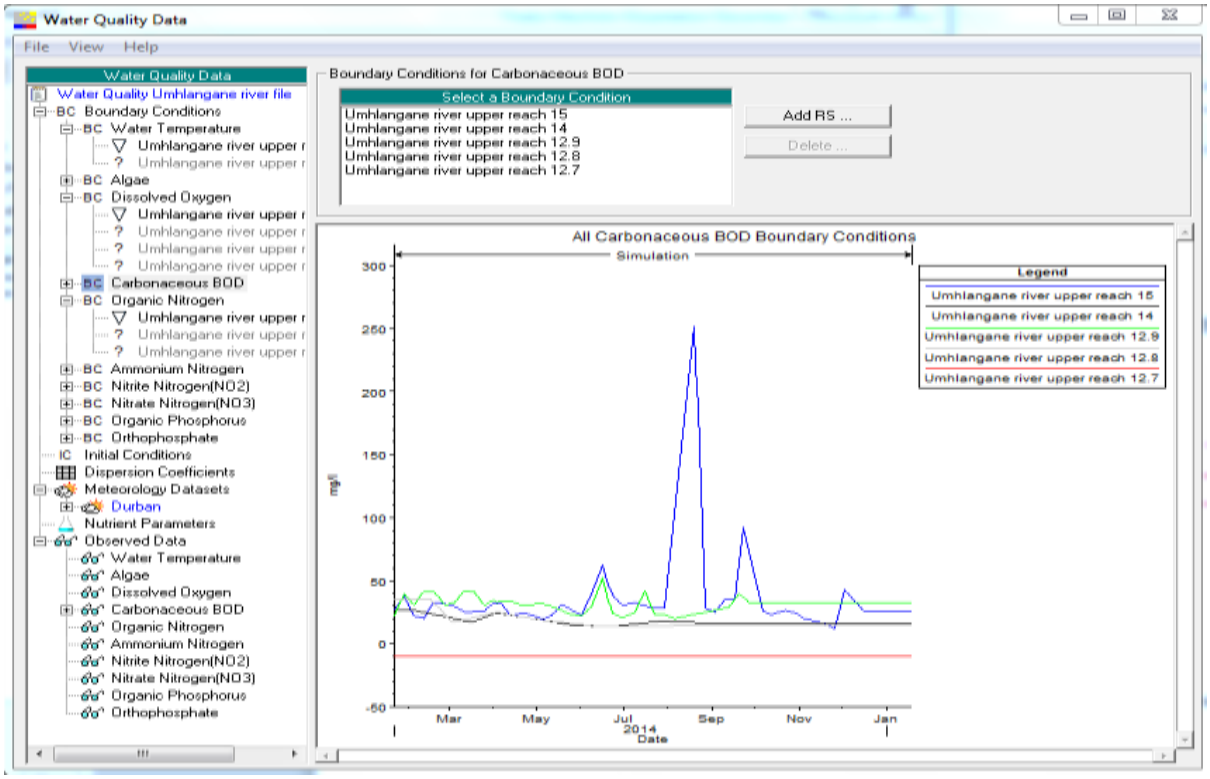

Figure 4.6 HEC-RAS parameters boundary conditions

4.5 HCIS - Model Parameters

The trial and an error approach was used in estimating the BOD and COD decay rates, to calibrate the model to best fit the simulated results with the observed data recorded. For consistency the total length of the river was divided into various common reaches for both HCIS and HECRAS.

Length of the reaches	R15 to R14	= 3.13 km (0 km to 3.13 km)
	R14 to R13	= 0.09 km (3.13 km to 3.22 km)
	R13 to R12.9	=11.28 km (3.22 km to14.8 km)
	R12.9 to R 12.8	= 0.5 km (14.8 km to 15.3 km)
	R12.8 to R 12.7	= 1.9 km (15.3 km to 17.2 km)
	R12.7 to R 12	= 0.1km (17.2 km 17.3 km)

The following were sampling points; Kwamashu Waste Treatment Works, R GANE 04, Monitoring Station, Northern Waste Treatment Works and R GANE 18 will now fall within R15 to R14, R14 to R13, R13 to R12.9, R12.9 to R 12.8 and R12.8 to R 12.7 respectively. Due to the inadequacy of data, calibration and validation of the results was done as a parallel process. The river reach was divided based on sampling points. The reaches between sampling points are discretised into series of hybrid mixing units of size Δx as per Equation 3.23. Table 4.2 consists of unique model parameters used for different reaches for the HCIS model. The initial

concentration of the BOD and COD are entered as the average values from the data obtained from the Ethekweni Water Services for each reach.

Table 4.3 HCIS parameters for calibration and validation

	Reaches				
Parameters	**R15 to R14**	**R14 to R13**	**R13 to R12.9**	**R12.9 to R12.8**	**R12.8 to R12.7**
COD (mg/L)	70	36	50	64	39
BOD (mg/L)	35	18	25	32	19.5
Flow velocity (m/min)	8.8	8.8	8.8	8.8	8.8
D_L (m^2/min)	212.58	212.58	212.58	212.58	212.58
Pe	8.36	8.36	8.36	4.36	8.36
$K_{1(BOD)}$ (1/min)	0.001	0.001	0.0019	0.001	0.001
$K_{1(COD)}$ (1/min)	0.0015	0.0015	0.019	0.0015	0.0015
$K_{2(reaeration)}$(1/min)			0.22		
No of observation	15000	15000	1600	1500	15000
Time step interval (min)	1	1	30	1	1
Reach length (m)	3130	3220	11280	500	1900
Number of Hybrid units	15	10	54	4	8
Size of Hybrid unit	201.951	201.951	201.951	105.324	201.951
Saturation DO Level (mg/L)	-	-	6	-	-
Initial DO Deficit (mg/L)	-	-	2	-	-

4.6 Root Mean Square Error

To test the performance of the water quality simulation parameters with the observed data, a statistical method known as the root mean square error is commonly used (Najafzadeh *et al*., 2013; Najafzadeh and Azamathulla, 2013).

$$\text{RMSE} = \sqrt[2]{(\Sigma(\text{Oi,j} - \text{Pi,j})^2 / \text{m})} \quad (4.2)$$

where $O_{i,j}$ equals to observed values, $P_{i,j}$ equals to predicted values and m is the number of pairs of predicted and observed values of the state variables.

4.7 Summary

The study area was located using google earth from which channel properties and the length of the river were measured. The sampling points where observed data was collected by Ethekweni Water Services are shown in the aerial photograph of the google earth. The pollution level of Umhlangane River as shown in this chapter was successfully presented on the BOD, COD and DO graphs at different stations. Despite the observed data being found to be discrete and sparse, after consolidating this data the determination was made that the water quality status of the Umhlangane River is poor and needs urgent attention. The sample collection time intervals of the observed data were conducted randomly at various sampling points by Ethekweni Water Services. The time interval inconsistencies resulting from labour costs and manpower shortages has led to the situation where some of the data turned out to be undesirable for water quality modelling at some of the reaches. One of the shortcomings of the supplied data concerns the dissolved oxygen samples that were recorded only at one single sampling point, despite being one of the most important water quality indicator parameters.

Both the HCIS and HEC-RAS were set-up by transforming models into Umhlangane River site working models that can be executed to simulate the desired water quality results. The comprehensive meteorological daily data of temperature, rainfall, wind speed and humidity from the nearest weather station to the river under study were analysed for HEC-RAS modelling input. The channel geometric data obtained was also used to calculate the re-aeration rate constant and the dispersion coefficient. The two models (HECRAS and HCIS) were calibrated to best fit the actual observed recorded data in terms of BOD, COD and DO. The root mean square was used to test the performance of the models' water quality simulation results using the observed data.

CHAPTER FIVE

RESULTS AND DISCUSSIONS

5.1 Introduction

This chapter presents the water quality simulation results for Umhlangane River generated using HEC-RAS and HCIS. The results were simulated based on the methodology and executional procedures of each model as described in the previous two chapters. The extraction of the simulation results matching dates with the recorded data is done for comparison. The simulation results are plotted and compared with the actual recorded data to validate and evaluate the performance of both the modified HCIS and HEC-RAS model. The initial behavioural response of the HCIS model is analysed separately, due to the unique model simulation output results. The statistical method known as the root mean square is further applied to estimate and consolidate the error between the simulation and the actual recorded data. Since Ethekweni Water Services collected field samples of COD only, the relationship of COD and BOD given by equation 4.1 is used to convert COD to BOD.

The simulation results for each model were produced reach by reach in terms of BOD and COD, depending on the data available for calibration. The dissolved oxygen is only simulated for reach R13 to R12.9, since it was the only reach with DO observed data available for calibration and validation. The water quality simulated parameters for each model were analysed and plotted on the same axis reach by reach. A set of common reaches for both the HEC-RAS and the HCIS models were proposed to create a suitable platform for comparison of the water quality simulation parameters of the models. The calibration of the models in the previous section was intended to adjust the model parameters to optimal simulation conditions until the predicted values and measured concentration data were in agreement. The purpose of model calibration was not solely for the model parameters, but also to reproduce the pollution loads released into the Umhlangane River

5.2 HCIS Initial Response

The BOD and COD results generated by HCIS for various reaches are depicted in Figures 5.1 to 5.8. The simulation results are plotted separately for each reach in order to illustrate the models' initial behaviour in simulating pollutants. The BOD concentrations increase with time at different rates for different reaches as pollutants are introduced. The variation is due to different decay and re-aeration rates assigned to each reach to match the observed data parameters. For the average reaches' input, the constant BOD concentration is attained in less than three hundred minutes for

all other three reaches except for R12.9 to R 12.8 where it is reached in less than hundred minutes. Similarly the COD concentrations become constant after four hundred minutes for the first reach (R15 to R14) and for the other three in less than two hundred minutes.

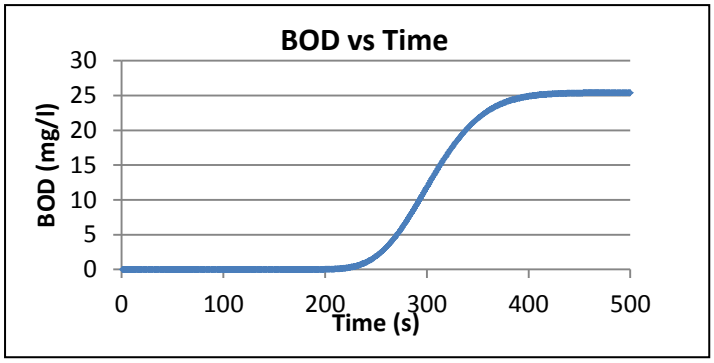

Figure 5.1 HCIS BOD - R15 to R14

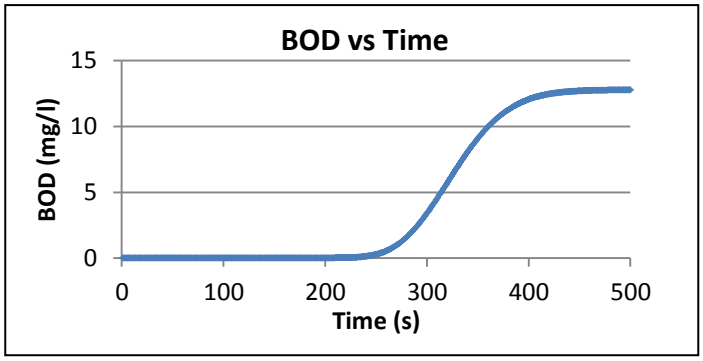

Figure 5.2 HCIS BOD - R14 to R13

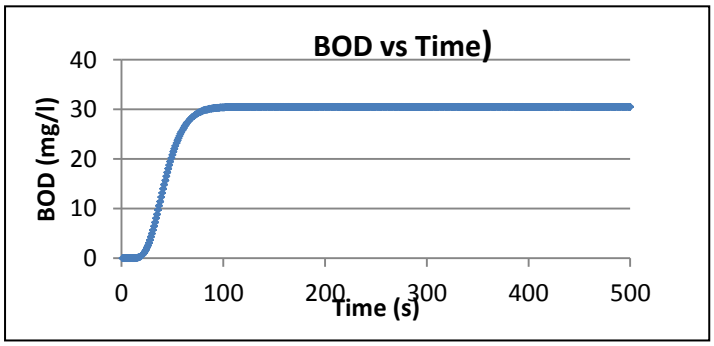

Figure 5.3 HCIS BOD - R12.9 to R12.8

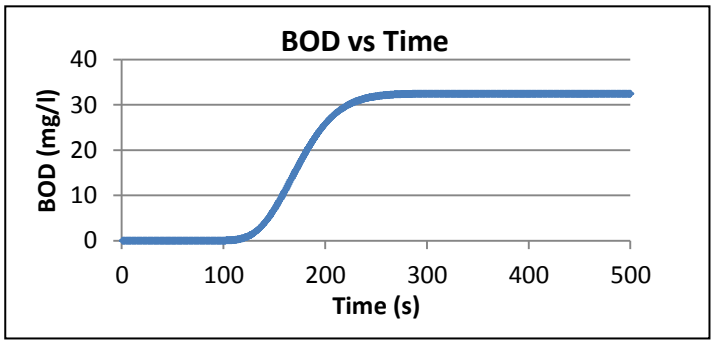

Figure 5.4 HCIS BOD - R12.8 to R12.7

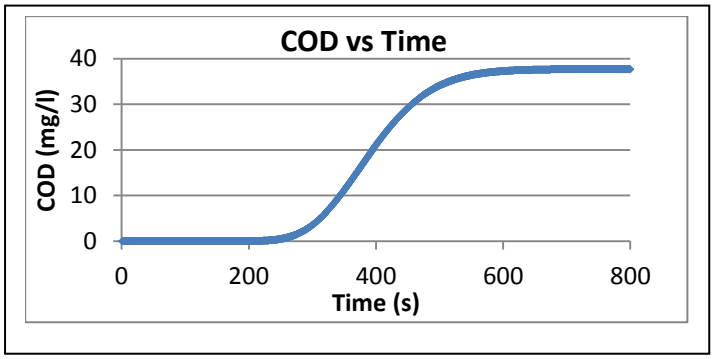

Figure 5.5 HCIS COD - R15 to R14

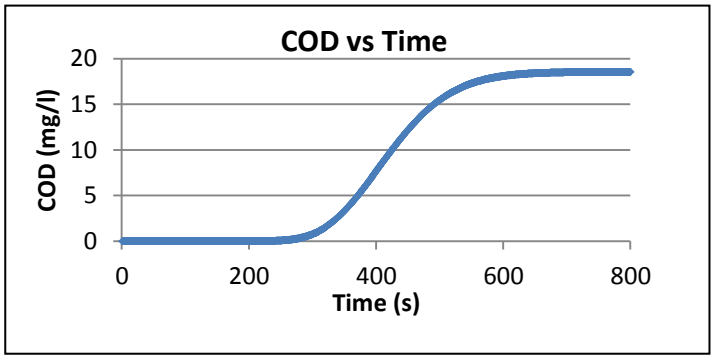

Figure 5.6 HCIS COD - R14 to R13

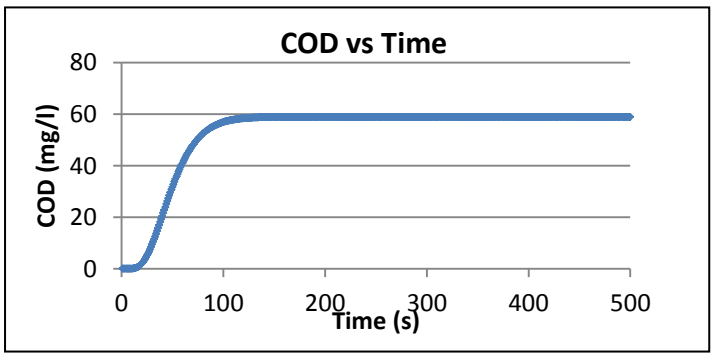

Figure 5.7 HCIS COD - R12.9 to R12.8

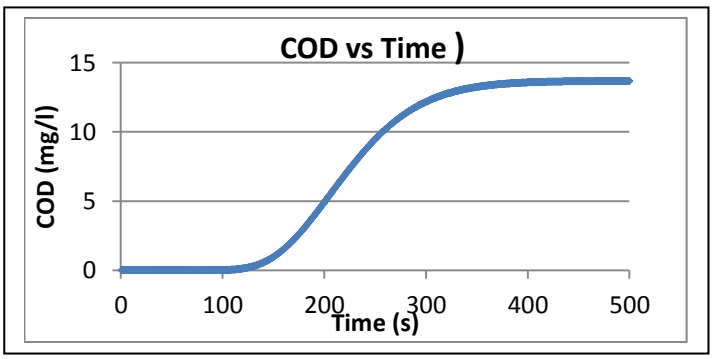

Figure 5.8 HCIS COD - R12.8 to R12.7

5.3 HCIS Simulation Results – COD

The HCIS model was run separately for each day, per reach at the various points of interest using the model parameters in Table 4.2. In HCIS model, the simulation was generated per minute as described in the previous section. The maximum constant values attained are plotted, depending on the amount of pollutants introduced into a river reach. In all reaches the maximum constant output values occurred under a period of 1440 minutes, which is less than a day. The graphs below depict the comparison of the HCIS model's simulation results and the observed data. The challenge here was with the mismatch of the observed recorded data dates at the beginning and the end of each reach. For accuracy, if the observed data recorded at a certain day is used as an input data, there must be an observed data at the end of the same reach, recorded for the same day that can be used for calibration and validation of the model. To establish the model's behaviour and performance, the simulation values before and after each observed values are plotted in the graphs. The behaviour of the HCIS model simulated values in Figure 5.9 to 5.10 appears to follow similar trend observed of the actual recorded values.

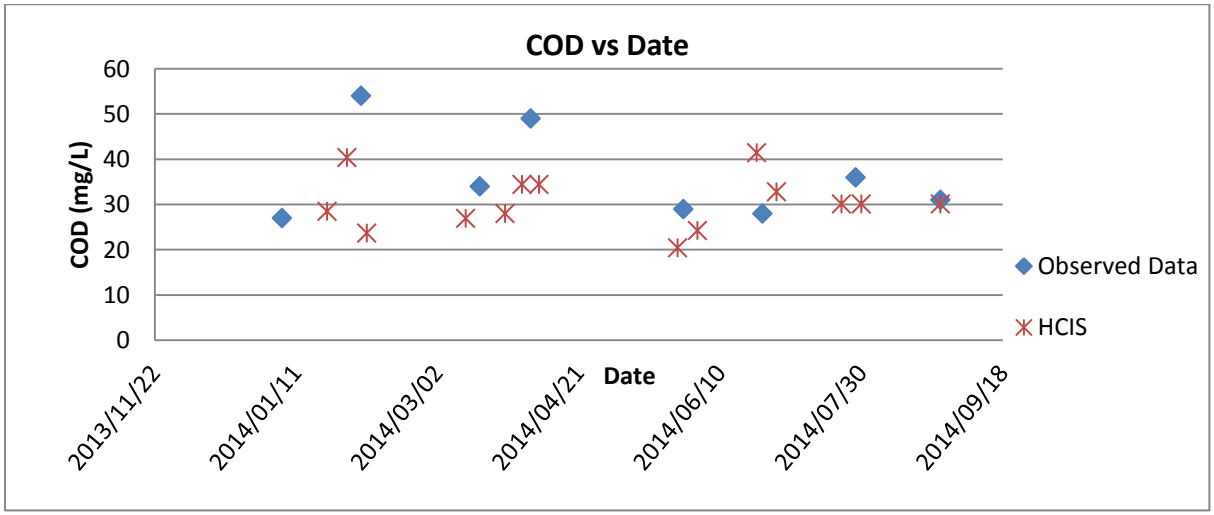

Figure 5.9 HCIS COD R15 to R14

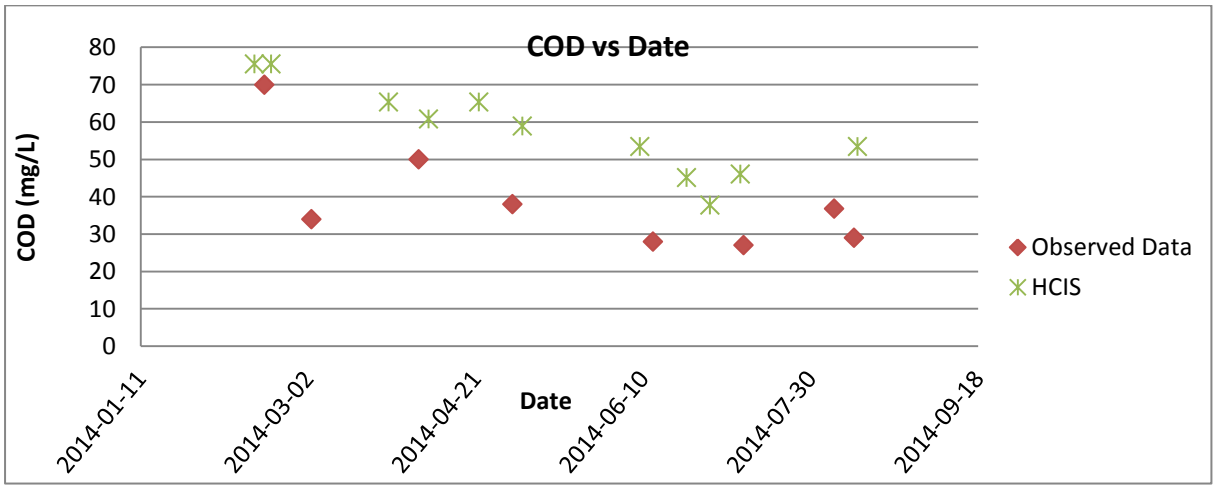

Figure 5.10 HCIS COD R12.9 to R12.8

5.4 HEC-RAS Simulation Results – BOD and COD

To assess the performance of the HEC-RAS model, the simulation results are plotted on the same axis with the observed data reach by reach. The BOD and COD simulated parameters for the HEC-RAS model were generated per day for a period of almost one year. The HEC-RAS simulation results (refer to Appendix D) that matches both the dates and times of the observed data were extracted for comparison. These were plotted, and are shown in figures 5.11 to 5.18. The HEC-RAS model performed well as the simulation results are in agreement with the actual recorded data. There is an increase of pollutants loading washed into Umhlangane River at the beginning of July. This is due to the rainfall that occurred for four consecutive days from 6 to 10 July (refer to Appendix B –Table B1) as seen in Figure 5.11 and 5.12 below.

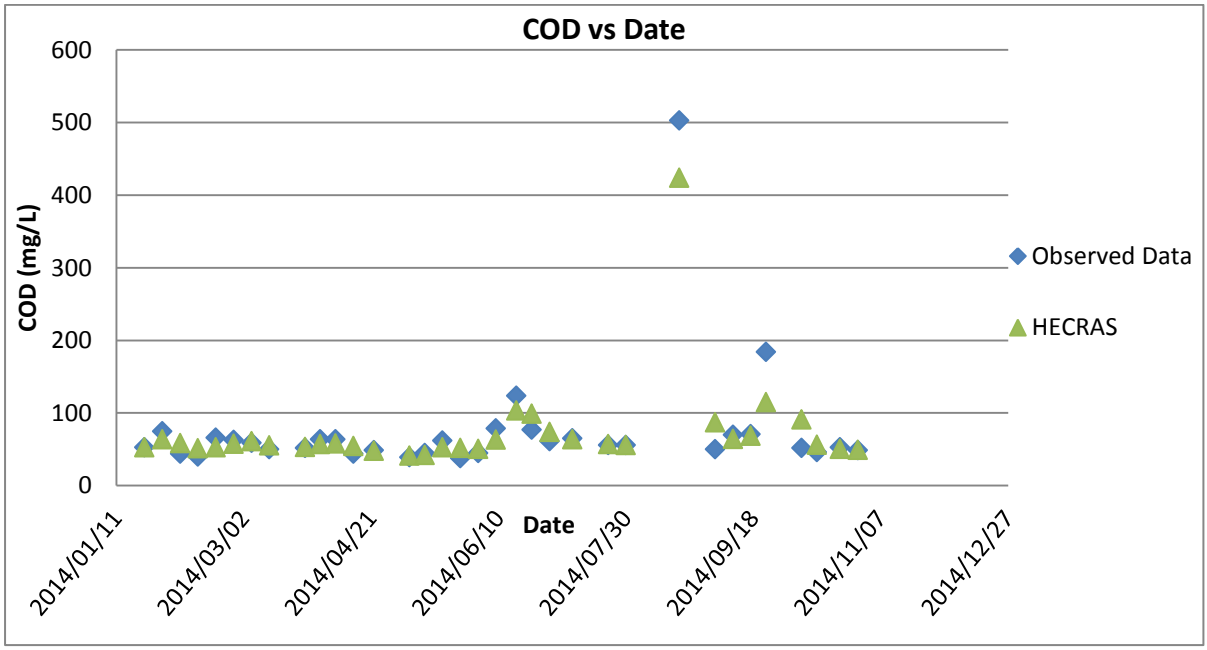

Figure 5.11 HEC-RAS COD - R15 to R14

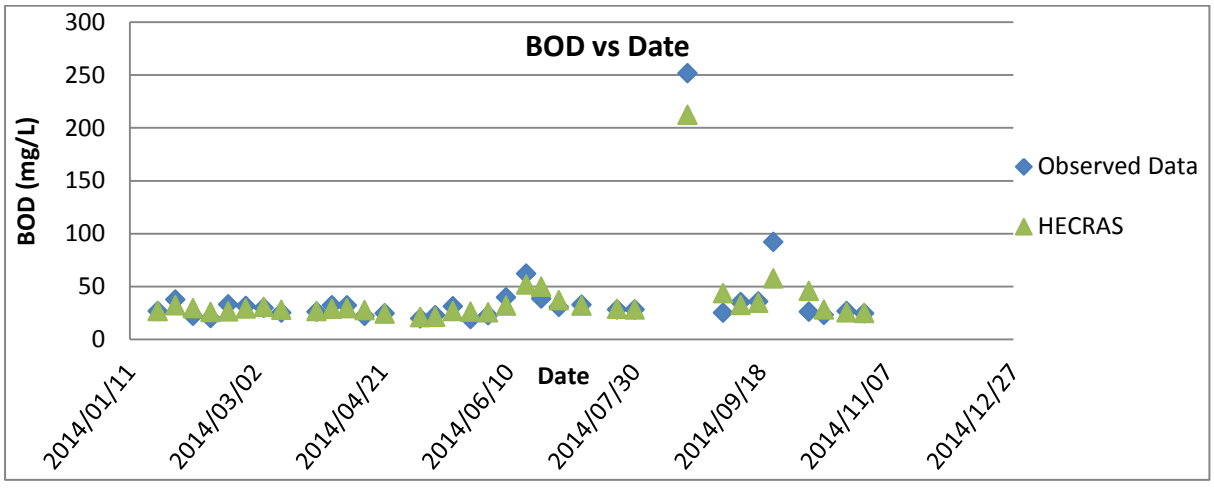

Figure 5.12 HEC-RAS BOD - R15 to R14

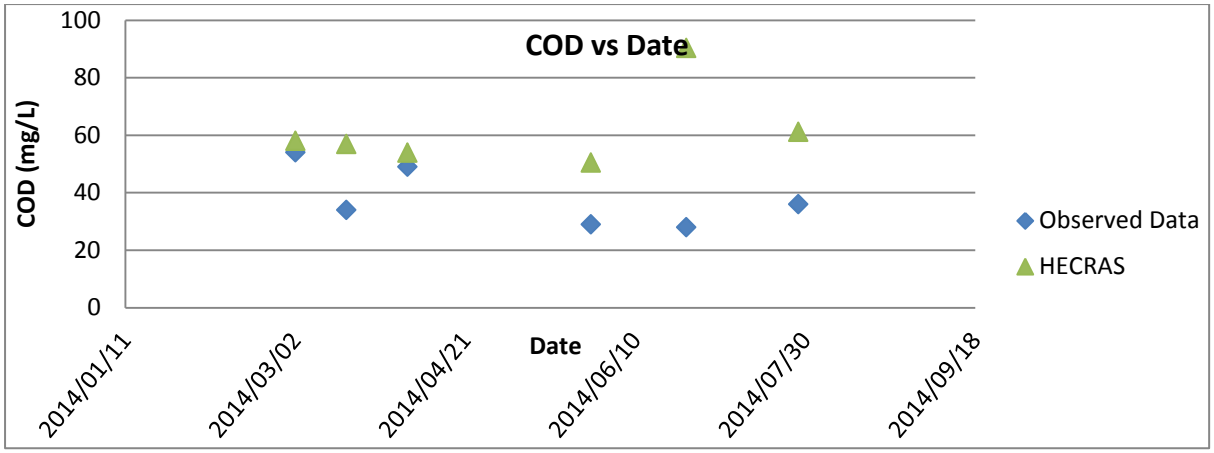

Figure 5.13 HEC-RAS COD - R14 to R13

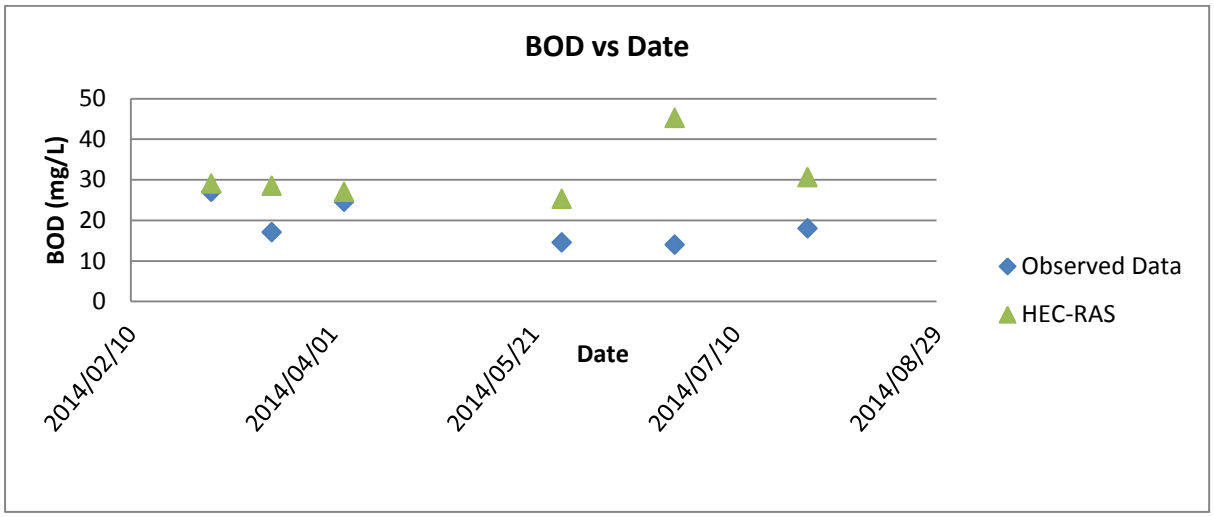

Figure 5.14 HEC-RAS BOD - R14 to R13

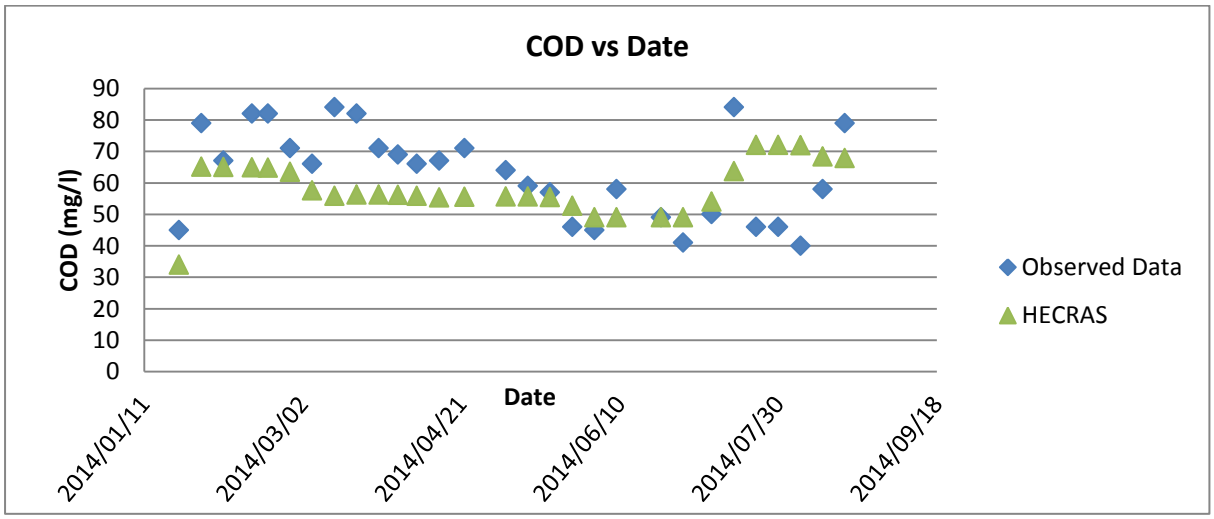

Figure 5.15 HEC-RAS COD - R12.9 to R12.8

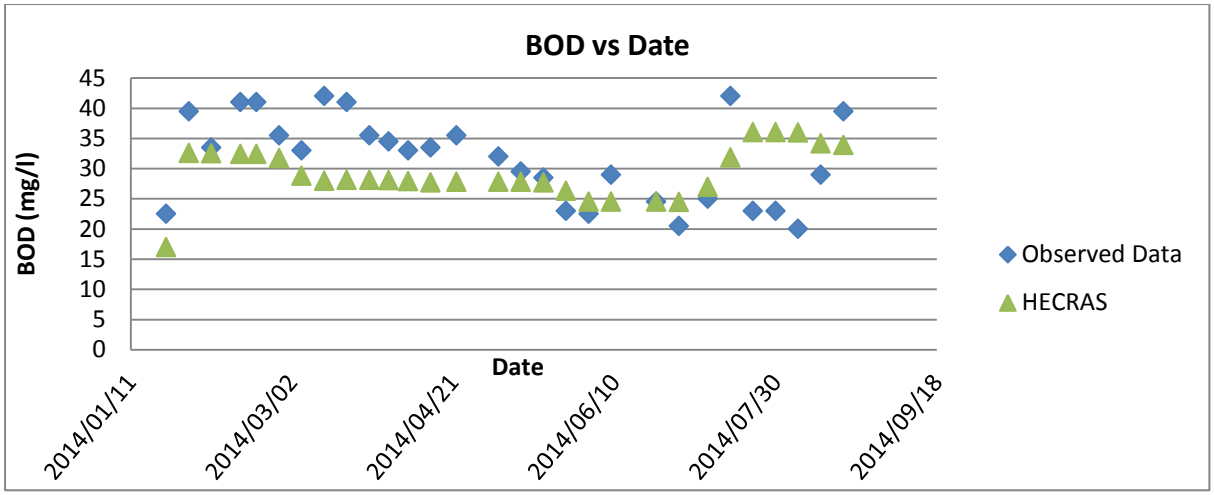

Figure 5.16 HEC-RAS BOD - R12.9 to R12.8

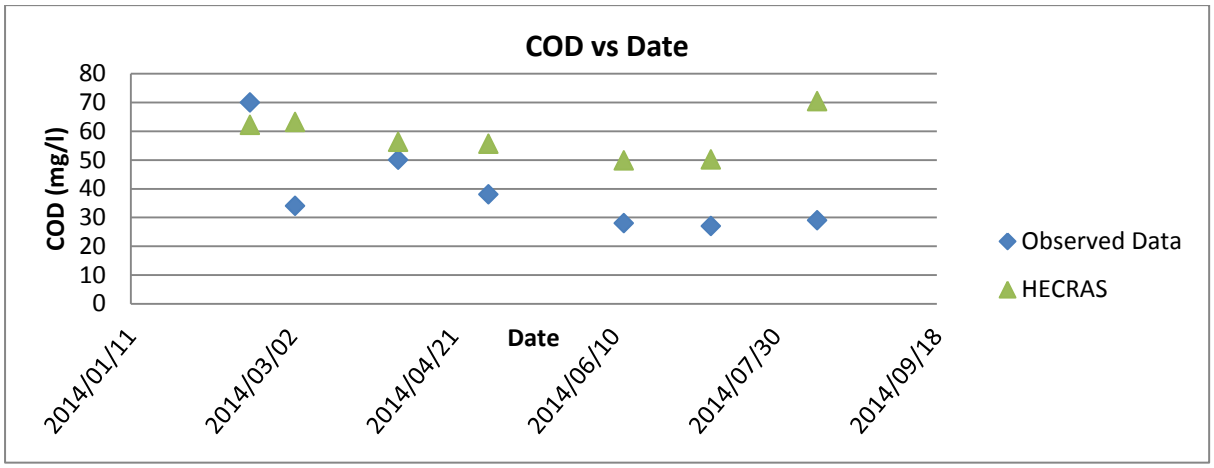

Figure 5.17 HEC-RAS COD - R12.8 to R12.7

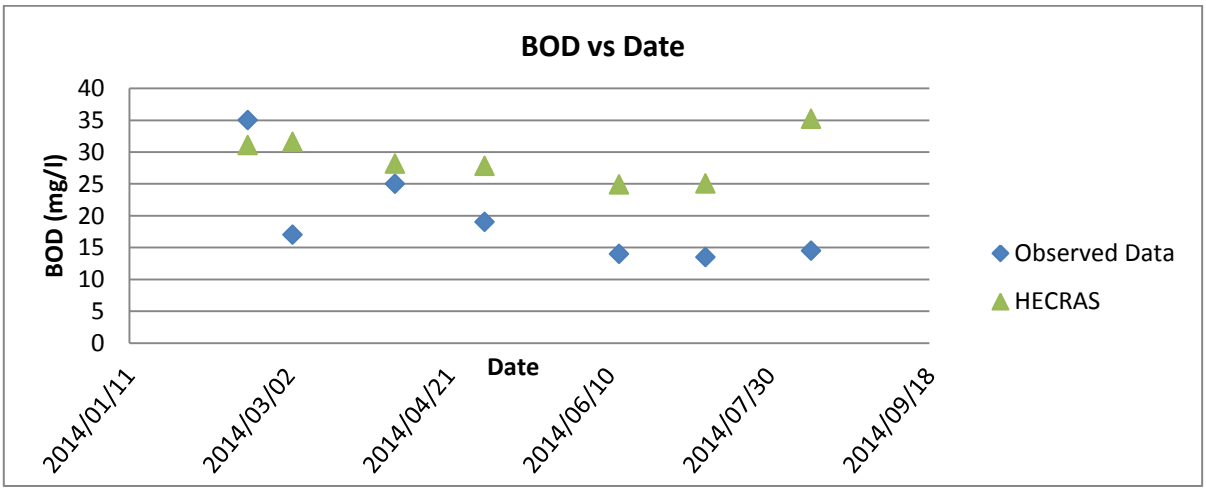

Figure 5.18 HEC-RAS BOD - R12.8 to R12.7

5.5 HEC-RAS and HCIS Simulation Results – DO

There was no observed data available for dissolved oxygen by Ethekweni Water Services at the other four stations except for R13 to R12.9. The observed data was supplied in time steps of 30 minutes, in order for comparison, both models (HEC-RAS and HCIS) time steps were changed to 30 minutes to match observed data time step. The simulation results of DO by both the HEC-RAS and HCIS models are shown Figure 19. The simulation results of both HCIS and HEC-RAS appear to produce average values of the periodic observed dissolved oxygen data.

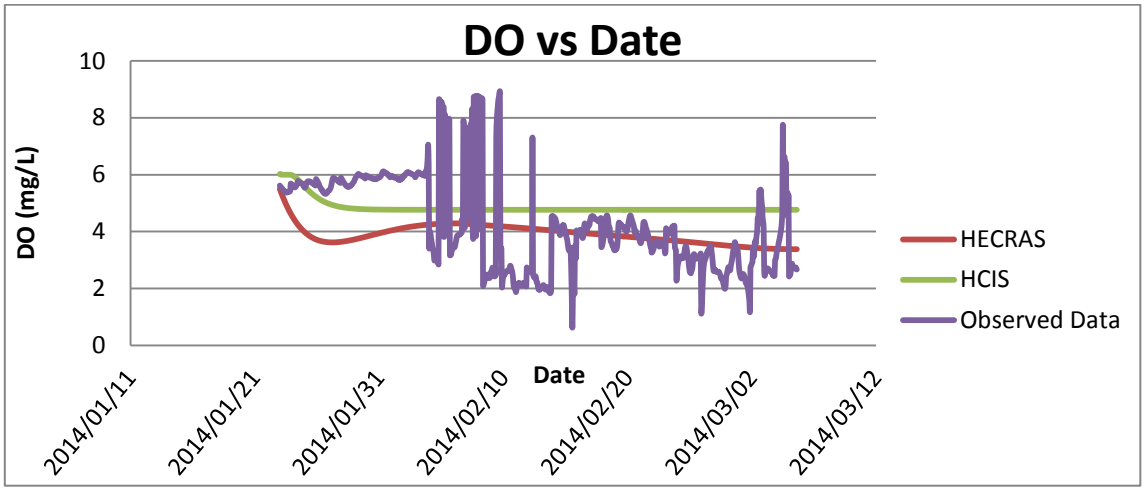

Figure 5.19 HCIS and HEC-RAS DO - R13 to R12.9

The plots satisfactorily demonstrate the capabilities of HEC-RAS and HCIS models to reproduce observed DO water quality profiles for Umhlangane River. The reproduction of the DO observed data by HEC-RAS is quite acceptable despite of having only one automated continuous water quality sampling station. With such additional stations or continuous water sampling over a shorter period of time, performance of the HCIS model could be tested for further possible improvement.

5.6 Root Mean Square Error

The Root Mean Square Error (RMES) from Equation 4.2 is used to test the performance of the models (refer to Appendix D) and the summarised errors between simulation results and observed data of BOD, COD and DO are shown in Table 5.1. The RMSE was not used where there is a mismatch of data dates for HCIS; however the trend behaviour of the model is shown in the next section between observed data and simulation results. The HCIS model performed well but did not produce oscillating results where there was an immediate variation of the observed results. The HEC-RAS model produced results of a better quality showing acceptable varying simulation

parameters profiles, the errors seems to reasonable and do not change much with the varying observed data.

Table 5.1 Root Mean Square Errors of simulated parameters

Root Mean Square Error (RMSE) (mg/L)						
	HCIS (COD)	**HEC-RAS (COD)**	**HCIS (BOD)**	**HEC-RAS (BOD)**	**HCIS (DO)**	**HEC-RAS (DO)**
R15 to R14	-	22.110	-	11.055	-	-
R14 to R13	-	30.409	-	15.205		
R13 to 12.9	-	-	-	-	1.693	1.605
R12.9 to R12.8	-	14.916	-	7.458	-	-
R12.8 to R12.7	-	23.856	-	11.928	-	-

The Figures 5.20 to 5.21 below depict the maximum BOD and COD concentrations of the observed data per station at the end of each reach down Umhlangane River.

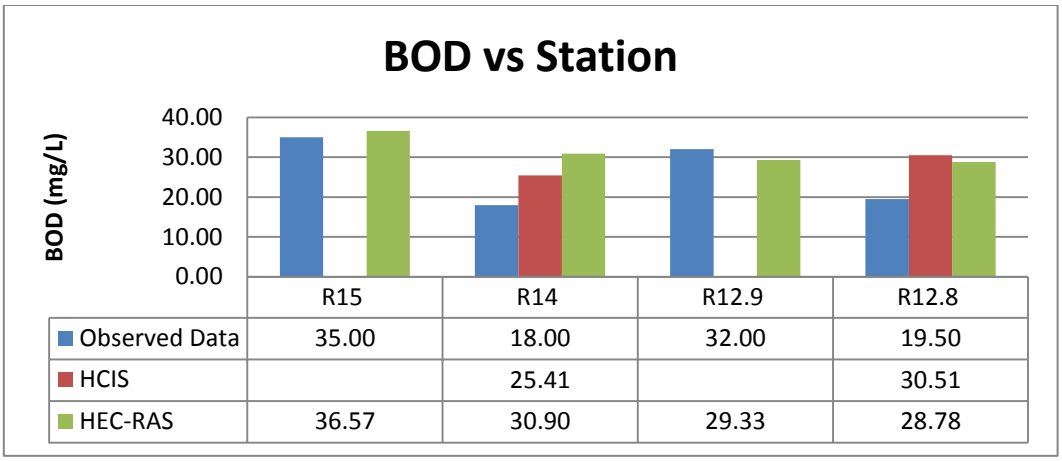

Figure 5.20 BOD Concentrations per Reach

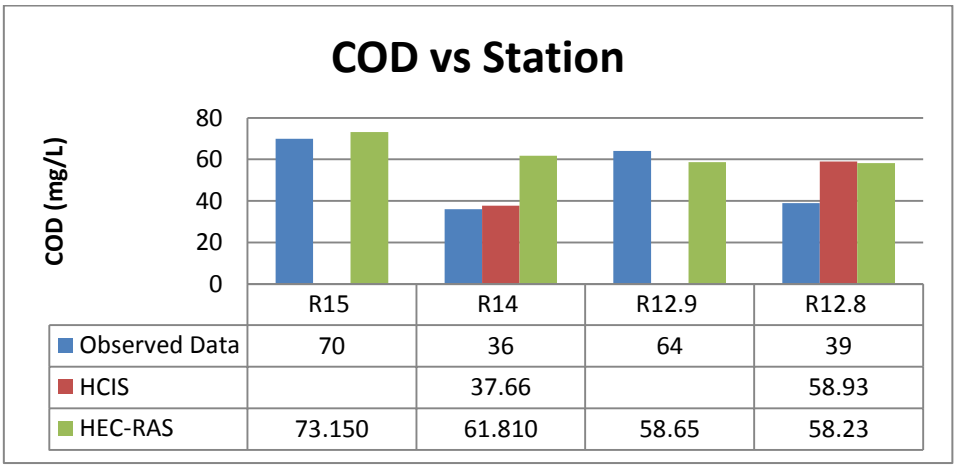

Figure 5.21 COD Concentrations per Reach

Figure 5.20 and 5.21 from the two graphs above show that the pollutants' concentration after the third station increases instead of decreasing as being diluted. This is due to the wastewater treatment works built at the third station, which is meant to reduce water deterioration. There is a possibility that chloramines used for disinfection may have resulted in excessive growth of nitrifying bacteria polluting water. The simulation data plotted in the graphs above does not contain any data for the HCIS at station R15 and R12.9, because the actual recorded data at these stations is used as the input data to generate output at R14 and R12.8 respectively.

5.7 Summary

The simulation results of the HEC-RAS model are in agreement with the actual observed data. The model was able to capture the main features of the concentration data in terms of DO, COD and BOD. The HCIS model produced DO, BOD and COD predicted values that are reasonably close to the observed data. Hence, the model did not simulate well the observed data output where there is a rapid change of the concentration of pollutants. For the DO concentration, the profile is different, although each model is calibrated in the same way. In the HEC-RAS model, the difficulty was with the insufficiently observed DO data required for upstream boundary conditions. It needs to be remembered that the mass-balance in the model is closed and by calibrating with incomplete data it is difficult to find a good fit for all the parameters. The DO predictions of both models seem to give average values of the observed results.

The deviation between the observed data and simulation results of the two models (HEC-RAS and HCIS) are due to the observed data consisting of a single collected sample at each sampling point, rather than multiple samples to assess variability. If the model simulation is established based on daily data, the observed DO data collected from the field may differ, depending on the samplings' collection measurement time during the day. The amount of DO concentration decreases at night due to temperature differences and low rates of photosynthesis. The important parameters that affect dissolved oxygen, such as organic nitrogen and ammonium nitrogen, were not available. In spite of these challenges, the modelling simulation results were satisfactory considering the obstacles one had to overcome, in particular a severe shortage of data. This is a common problem in many rivers in developing countries such as South Africa. The comparison of the water quality simulations produced by the HCIS and HEC-RAS models for Umhlangane River in terms of BOD and COD and DO generated some useful profiles. It is concluded that future predictions by these models can be used to assist in bettering the water quality management of the Umhlangane River.

CHAPTER SIX

CONCLUSION

The performance of the HCIS and HEC-RAS models were evaluated by comparing the water quality simulation generated by both models to the observed data. The simulation results were then assessed in view of the possibility of improving water quality of Umhlangane River. The HEC-RAS model was employed as one of the models in this study due to the good water quality analysis capabilities that it has displayed over the years. The performance of the HCIS was also evaluated as one of the developing models, to be improved further to meet modern water quality challenges. In meeting the objectives of this study, the HCIS model was upgraded by modifying it to incorporate BOD and COD into the original mass-balance equation (Kumarasamy, 2015) as presented in chapter three. The new modified HCIS model was tested and successfully investigated by performing a water quality analysis of Umhlangane River. The analysis of the simulated water quality results generated by this model yielded some promising outcomes when compared to the actual recorded data (as described in chapter five). During calibration and verification of the results for the HCIS model, it was discovered the model works well when the Peclet number is more than four.

The modified HCIS model with the inclusion of BOD and COD into the mass balance equation yielded positive outcome at the upper reach, where there was an average agreement of seventy percent between simulation results and the observed data. With this kind of performance, any user who chooses to employ this model should be able to run it with some degree of confidence in predicting future water quality of the river under investigation. However, serious caution needs to be exercised when considering the variation of re-aeration, decay rates of BOD and COD coefficients. The advantage with this model is that any specific point of interest along the river could be chosen and analysed in terms of DO, BOD and COD. The disadvantage with this model is that the BOD and COD inputs of the pollutants are assumed to be of average constant values. This neither reflects nor takes into account the variations and fluctuations of the dynamic pollutants' changes taking place at different times. The model is flexible enough and has the capacity for the addition of any other parameters.

The water quality parameter results simulated by the HECRAS model were of good quality in terms of the root mean square error when compared with the actual recorded data. The reason being that the model is capable of handling varying concentrations of pollutants' inputs and takes into account the direct water quality effects of nutrients in streams and rivers. The model was able to simulate the observed water quality concentrations of various water quality parameters along the Umhlangane River with hydraulic simulation outputs at each specified time. Moreover, the model reproduces temporal and spatial distributions of various parameters. The predictions were based on the collective effects of biological, hydraulic, and chemical processes involved. A major advantage of the HECRAS model is that it requires less computational effort, which makes it more desirable for projects where there is a large amount of data to be processed.

Due to the complexity of the processes involved in river systems, continuous research is essential by water quality researchers to seek to develop water quality models that will be able to incorporate the most relevant process descriptions.

Future work

(i) To incorporate nutrients dynamics into the HCIS model;

(ii) To factor in non-point water pollution to account for the discharges associated with sub-catchments of the river - such as drainage overflows and rainfall - that has the potential to make changes in the water quality of our river;

(iii) To improve HCIS model by considering channel and flow variables.

6.0 References

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Appendix A

Kwamashu WWTW				
Date	**COD (mg/L)**	**[Nitrate + Nitrite] (mg/L)**	**Ortho phosphate (mg/L)**	**pH**
22/01/2014	53	2.9		7.54
29/01/2014	75	0.29		7.62
05/02/2014	44	2.6	4.4	7.53
12/02/2014	40	3.5	2.6	7.54
19/02/2014	66	3.3	3.2	7.51
26/02/2014	63	1.2	0.74	7.62
05/03/2014	59	0.86	1.1	7.51
12/03/2014	50	2.4	2.2	7.36
26/03/2014	52	3.2		7.35
01/04/2014	64	2		7.49
07/04/2014	64	4.9	1.8	7.43
14/04/2014	44	3.7		7.4
22/04/2014	49	3.6	3.9	7.28
06/05/2014	39	1.5	1	7.3
12/05/2014	45	1.6	2.4	7.34
19/05/2014	62	2.9	11	7.36
26/05/2014	38	2.4	1.9	7.44
02/06/2014	45	2.8	3	7.54
09/06/2014	79	4.1	5.8	7.31
17/06/2014	124	4.8	4.4	7.28
23/06/2014	77	8.5	3	7.43
30/06/2014	61	5.2	2.9	7.4
09/07/2014	65	5	3.6	7.48
23/07/2014	56	3.1	0.17	7.25
30/07/2014	56	5.8	2.8	7.17
20/08/2014	503	3.1	9.6	7
27/08/2014	56	3.8	4.1	7.88
03/09/2014	50	5.8		7.12
10/09/2014	70	4.9	2.4	7.2
17/09/2014	71	3.6	2.6	7.13
23/09/2014	184	4.8	2.8	7.23
07/10/2014	52	3.7	2.9	6.97
13/10/2014	46	2.6	2.5	7.27
22/10/2014	53	1.8	1.4	7.24
29/10/2014	49	1.5	1.8	7.27
04/11/2014	40	1.6	2.4	7.16
17/11/2014	33	3.6	4.3	7.14
26/11/2014	24	0.42	1.7	7.04
03/12/2014	85	3.9	3.4	7.16
09/12/2014	71	5.5	2.9	7.15
17/12/2014	51	4	1.2	7.13
13/01/2015		5.6	1.3	7.19
19/01/2015		4.8	1.8	7.19

Table A1 Kwamashu WWTW observed data

Northern WWTW				
Date	**COD (mg/L)**	**[Nitrate + Nitrite] (mg/L)**	**Ortho phosphate (mg/L)**	**pH**
06/01/2014				
08/01/2014	85	9.2	3.8	7.18
15/01/2014	55	7.5	2.6	7.55
22/01/2014	45	9.7		7.33
29/01/2014	79	7.3		7.42
05/02/2014	61	5.3	2.9	7.36
12/02/2014	82	8.7	3.5	7.29
19/02/2014	82	9.1	1.2	7.37
26/02/2014	71	5.9	2.2	7.37
05/03/2014	66	7.3	1.5	7.33
12/03/2014	84	7.8	7	7.29
19/03/2014	82	10	2.7	7.4
26/03/2014	71	8.2		7.35
01/04/2014	69	8.2		7.34
07/04/2014	66	11	2.3	7.32
14/04/2014	67	6.6		7.4
22/04/2014	71	10	2.5	7.27
05/05/2014	64	5.4	3.8	7.42
12/05/2014	59	9.5	2.2	7.27
19/05/2014	57	6.6	3.3	7.28
26/05/2014	46	5.6	3.2	7.2
02/06/2014	45	10	6	7.21
09/06/2014	58	15	2.5	7.64
17/06/2014	102	8.8	2.6	7.25
23/06/2014	49	17	4.2	7.19
30/06/2014	41	13	3.2	7.25
09/07/2014	50	9.4	1.9	7.29
16/07/2014	84	11	4.8	7.31
23/07/2014	46	4.1	0.84	7.25
30/07/2014	46	9.2	2	7.5
06/08/2014	40	9.8	1.8	7.33
13/08/2014	58	4.5	5	7.39
20/08/2014	79	6.7	4.3	7.32
27/08/2014	66	8.6	4.6	7.3

Table A2 NWWTW observed data

R GANE 04				
	COD (mg/L)	**[Nitrate + Nitrite] (mg/L)**	**Ortho phosphate (mg/L)**	**pH**
06/01/2014	27	2.4	0.3	7.84
03/02/2014	54	2.2		7.95
17/03/2014	34	3.0	0.09	7.62
04/04/2014	49	3.2	0.48	7.84
28/05/2014	29	2.7	0.3	7.6
25/06/2014	28	3.7	0.22	7.59
28/07/2014	36	2.4	0.4	7.69
27/08/2014	31	2.3	0.45	7.81

Table A3 R Gane 04 observed data

R GANE 18				
Date	**COD (mg/L)**	**[Nitrate + Nitrite](mg/L)**	**Ortho phosphate (mg/L)**	**pH**
17/02/2014	70	0.64	2.2	7.52
03/03/2014	34	2.3	3.2	7.54
04/04/2014	50	2.2	0.74	7.59
02/05/2014	38	1.7	1.2	7.5
13/06/2014	28	3.2	1.5	7.47
10/07/2014	27	1.9	1.1	7.43
12/08/2014	29	1.8	1.2	7.4

Table A4 R Gane 18 observed data

APPENDIX B

Table B1 Meteorological Data – January to February 2014

	January 2014								February 2014							
Day	**T_{ave} (ºC)**	**T_{max} (ºC)**	**T_{min} (ºC)**	**atm (kPa)**	**Humidity (%)**	**Rainfall (mm)**	**V_{ave} (km/h)**	**V_{max} (km/h)**	**T_{ave} (ºC)**	**T_{max} (ºC)**	**T_{min} (ºC)**	**atm (hPa)**	**Humidity (%)**	**Rainfall (mm)**	**V_{ave} (km/h)**	**V_{max} (km/h)**
1	25.1	28.7	21.4	101.29	73	0	7.6	13	25.3	28.1	22.4	1011.5	75	0.51	7.6	13
2	26.3	29.8	22.7	101.15	74	0	8	13	25.7	28.1	24.3	1011.9	73	0.25	9.3	16.5
3	26.4	29.8	24.1	101.28	75	0	13	22.2	24.3	27	22	1014.9	76	1.02	7.6	18.3
4	25.6	29.5	22.4	101.03	73	0	11.5	16.5	25.9	28.6	21	1009.6	74	0.51	10.6	18.3
5	25.7	29	21.3	100.33	73	0	13	22.2	25.9	29.5	24.4	1005.4	83	0	7.4	13
6	26.2	29.9	21	100.47	76	0	5.4	11.1	25.9	30.2	23.9	1009.2	79	2.03	9.4	16.5
7	26.8	30.1	23.6	100.85	80	1.02	8.5	14.8	26.8	30.2	22.7	1011.4	74	0.51	10.2	18.3
8	26.2	30.1	24.1	101.22	79	12.95	11.7	18.3	26.2	30.2	23.7	1009	73	0.25	10.7	22.2
9	26.2	29.7	24.2	100.91	74	0	16.5	24.1	26.9	30.2	23.6	1009.6	71	0	7.2	13
10	25.9	29.9	23.3	101	76	11.94	11.1	18.3	27.3	30.4	23.7	1012.1	78	4.06	7.2	11.1
11	24.8	29.9	21.9	101.71	75	0.76	8.7	16.5	27.6	31.3	24.5	1009.9	69	0	12.6	20.6
12	26.9	31.1	23	101.29	78	0	14.1	22.2	26.4	31.3	22	1010.4	76	0	9.6	16.5
13	24.1	31.1	20.6	101.84	72	5.08	14.6	20.6	27.4	31.5	23	1012.3	77	0	10	18.3
14	22.4	26.8	19.7	101.9	77	6.1	8.1	11.1	27.7	31.5	24.9	1017.7	80	0	5.7	9.4
15	25.8	29	22.5	101.31	70	0.51	18.5	25.9	26.8	30.7	23.3	1018	74	0	6.9	14.8
16	25.9	29.3	21.2	101.6	76	0	13.9	20.6	26.3	30.6	21	1015.3	71	0	7.4	13
17	26.2	29.3	22.1	101.51	76	0	9.4	16.5	26.7	30.6	22.4	1015	67	0	13	20.6
18	24.8	29.1	22.8	101.56	82	0	6.9	14.8	26.3	29.9	21.8	1011.9	72	0	6.9	11.1
19	25	28.5	22.7	101.64	79	1.02	9.4	14.8	27.6	30.9	24.5	1011.3	72	0	8.1	11.1
20	26.2	28.7	23.9	101.59	80	11.94	13.5	18.3	27.3	31	23.4	1007.2	72	0	10.7	14.8
21	26.7	28.7	24.4	101.81	72	0	7.8	11.1	24.1	31	21.6	1016.2	75	5.08	14.1	20.6
22	25.8	28.7	21	101.62	73	0	13	24.1	24.7	27.7	20.9	1018.6	70	7.87	6.7	11.1
23	27.5	30.9	24.8	100.81	77	0	14.4	20.6	25.6	28	22.6	1016.4	76	0.25	6.7	13
24	27.7	33	23.8	100.69	75	5.08	10	18.3	26.4	30.2	24.4	1012.2	79	0.25	10.2	27.8
25	25.6	33	23.6	101.36	75	2.03	12.2	20.6	26.5	31.2	23	1011.7	69	7.87	14.3	31.7
26	26	29.1	21.9	101.68	69	0.51	8	14.8	24.4	31.2	21.2	1017.1	70	2.03	14.1	20.6
27	26.4	29.8	22.3	101.47	77	0	13.9	22.2	24.9	29.2	20	1013.8	66	0.25	8.1	11.1
28	27.3	30.5	24.8	101.1	76	0.51	17.6	24.1	26.9	29.8	24.5	1008	69	0	8.1	13
29	27.2	30.6	24	100.9	79	0	11.3	16.5								
30	23.9	30.6	23	101.27	86	0.51	9.3	13								
31	24.5	27.5	22.7	101.52	77	9.91	7.4	13								
Monthly Ave	**25.8**	**29.7**	**22.7**	**101.28**	**75.9**	**69.87**	**11.2**	**17.8**	**26.2**	**30**	**22.9**	**1012.4**	**73.6**	**32.74**	**9.3**	**16.4**

Table B2 Meteorological Data – March to April 2014

March 2014									April 2014							
Day	**T_{ave} (ºC)**	**T_{max} (ºC)**	**T_{min} (ºC)**	**atm (kPa)**	**Humidity (%)**	**Rainfall (mm)**	**V_{ave} (km/h)**	**V_{max} (km/h)**	**T_{ave} (ºC)**	**T_{max} (ºC)**	**T_{min} (ºC)**	**atm (kPa)**	**Humidity (%)**	**Rainfall (mm)**	**V_{ave} (km/h)**	**V_{max} (km/h)**
1	27.4	31.4	23.5	100.77	73	0.25	7.8	16.5	24.7	29.4	21.4	100.81	78	18.03	10.2	16.5
2	27.5	31.4	23.8	101.03	75	0	7.6	14.8	24.8	29.4	21.7	100.76	76	0.51	5.7	9.4
3	27.3	32.3	24.4	101.11	77	8.89	10.7	22.2	23.2	26.8	20.3	101.36	62	0	9.4	16.5
4	25.1	32.3	23.3	101.35	77	4.06	10	13	22.6	26.8	19.4	102.16	63	0	9.6	20.6
5	25.5	29	23.6	101.59	80	0.25	8.5	13	22.8	26.1	19.7	102.39	57	0.51	14.4	22.2
6	25.7	27.9	23.6	101.34	84	2.03	7.4	14.8	22.7	26.8	20	102.36	64	0	11.3	18.3
7	27.8	31.6	24.2	100.88	80	0.51	6.1	11.1	23.4	27.2	19.5	102.5	62	0	8.5	14.8
8	27.5	31.6	25.8	101.17	76	0	8.5	14.8	23.2	27.2	20	102.52	68	0	7.4	14.8
9	26.5	30.7	24.2	101.32	77	0	14.1	35.2	24.3	27.7	19.7	102.49	65	0	10.6	24.1
10	21.7	30	19.1	101.9	82	9.91	8.5	16.5	25.2	27.3	18.5	102.38	68	0	13	18.3
11	23.9	26.7	21.4	100.96	82	3.05	6.5	9.4	23.9	28.5	19.4	102.38	72	0	10.9	20.6
12	23.6	29.8	20.5	101.17	70	1.02	12.4	22.2	23.4	28.5	17.8	102.21	75	0	7.4	16.5
13	22.4	29.8	19.4	102.37	54	0.51	11.5	18.3	23.2	27.8	18.2	102.02	75	0	10.6	18.3
14	24.7	28.4	20.2	101.65	66	0	13.5	22.2	22.9	27.8	18.9	101.45	74	0	6.7	13
15	26.4	29	22	101.28	77	0	7.6	14.8	22.2	26.8	17.2	101.8	74	2.03	13.9	18.3
16	26.6	29	25.1	101.39	77	0	7.4	11.1	19	26.8	16.9	102.47	78	7.11	9.4	14.8
17	25.9	30.4	23.6	101.47	80	1.02	10.2	20.6	20.5	24	17.3	102.16	73	0.51	5.6	9.4
18	25.3	30.4	22.1	101.42	73	5.08	12.6	24.1	22.4	26	17.1	101.74	70	0	5.4	13
19	25.1	33.7	21.5	100.8	77	0.25	13.9	24.1	23.4	26.9	18.3	101.9	75	0	5.9	11.1
20	24.3	33.7	21.8	101.77	67	0.51	10	18.3	24.6	27.2	22.2	101.84	76	0	5.7	13
21	24.2	27.5	21.4	101.99	71	0	11.9	24.1	24.7	28.8	21	101.25	78	0	5.7	11.1
22	26	29.9	21.2	101.33	74	0	13	24.1	25.7	30.2	22.2	100.89	70	0	7.6	14.8
23	26.4	29.9	21.9	101.32	78	0	10.4	18.3	22	30.2	19	101.27	74	0.76	6.5	13
24	26.6	29.7	23.6	101.72	78	0	14.6	24.1	21.4	26.8	17	101.29	67	2.03	8.5	18.3
25	25.7	29.4	22.4	101.28	72	0	14.3	25.9	22.9	26.8	19.1	101.82	55	0.25	10.9	20.6
26	24.6	29.4	20.8	101.11	75	0.51	11.7	22.2	22.3	26.8	18.2	101.62	68	0	6.3	9.4
27	21.3	28.8	19.5	101.93	82	18.03	5.9	9.4	21.3	25.9	18.1	102.12	56	0	16.9	27.8
28	23.4	28.4	19.3	102.04	74	7.87	5.2	9.4	19.9	24.9	16.1	102.12	61	0	8.9	11.1
29	23.4	28.4	18.1	101.34	77	0	6.7	16.5	22	26.9	14.9	101.32	60	0	7.6	11.1
30	24.9	28.9	20.8	101.46	76	0	10.2	18.3	21.9	26.9	18.7	101.75	74	6.1	8.3	16.5
31	25.4	28.9	21.6	101.44	75	0	9.6	18.3								
Monthly Ave	**25.2**	**29.9**	**22.1**	**101.4097**	**75.4**	**63.75**	**9.9**	**18.3**	**22.9**	**27.3**	**18.9**	**101.8383**	**68.9**	**37.84**	**9**	**15.9**

Table B3 Meteorological Data May to June 2014

	May 2014								June 2014							
Day	**T_{ave} (°C)**	**T_{max} (°C)**	**T_{min} (°C)**	**atm (kPa)**	**Humidity (%)**	**Rainfall (mm)**	**V_{ave} (km/h)**	**V_{max} (km/h)**	**T_{ave} (°C)**	**T_{max} (°C)**	**T_{min} (°C)**	**atm (kPa)**	**Humidity (%)**	**Rainfall (mm)**	**V_{ave} (km/h)**	**V_{max} (km/h)**
1	22.4	26.9	18.2	101.72	70	0.25	10.2	25.9	21.6	28.9	15.4	100.89	66	0	8.5	18.3
2	22.7	26.9	18	101.92	69	0	10.9	20.6	21.1	28.9	19.2	101.45	78	0.51	6.9	9.4
3	23.3	26.6	17.1	101.82	78	0	8.7	14.8	20.7	24.1	17	101.19	76	0	8.5	13
4	23.5	28.7	18.1	101.3	77	0	8	18.3	21.7	30.3	14.4	100.37	57	0	7.2	13
5	21.2	28.7	16.4	102.29	63	0	14.8	18.3	19.5	30.3	14.8	101.03	73	0.51	11.5	14.8
6	18.7	23.6	16.4	102.95	72	0.25	5.6	9.4	17.2	24	14.8	102.41	41	0	14.6	24.1
7	20.6	24.9	14.9	102.09	69	0	8.5	18.3	16.8	22.5	12.2	102.78	53	0	9.8	13
8	21.7	25.3	16.6	101.52	77	0	7.8	16.5	18.2	24.1	10.2	101.81	57	0	8.7	18.3
9	22.4	27.3	17.6	100.99	72	0	8.1	20.6	17	24.8	10.4	101.22	53	0	4.8	7.6
10	21.5	27.3	19.8	101.62	75	0.51	5.7	11.1	18.4	24.8	13	102.51	50	0	15.4	25.9
11	20.3	24	18.6	101.6	81	17.02	4.4	9.4	17.1	22.5	12.8	102.95	58	0	7.8	13
12	20.8	26.1	17.3	101.6	62	0.25	7.4	9.4	16.2	23.4	12.7	102.46	61	0	6.9	11.1
13	19.9	26.1	17.6	102.27	70	0	9.1	18.3	17.7	24.6	13	101.85	47	0	7.6	14.8
14	21.1	25.6	16.1	102.11	68	0	10.2	16.5	19.2	24.6	12.9	101.05	41	0	10.2	14.8
15	20.6	25.6	16.1	101.49	73	0	9.3	14.8	21	24.4	16.6	100.72	59	0	7.8	13
16	21.6	25.7	17.2	101.11	67	0	11.5	20.6	20.2	24.7	15	102.01	57	0	8.7	16.5
17	21.2	25.7	18.3	102.21	55	0	12.6	22.2	20	24.7	17.1	102.09	70	0	7.2	11.1
18	18.3	25.1	16.4	102.84	68	0	7.6	14.8	19.8	23.9	14.2	101.35	65	0	9.3	16.5
19	19.6	24	14.9	102.17	70	0	7	11.1	20.1	24.9	17.7	102.04	50	0	14.4	27.8
20	22.2	26.2	15.1	101.25	66	0	6.9	16.5	16.9	24.9	12.6	103.02	39	0	6.5	9.4
21	21.6	26.2	17.9	102.02	67	0	13	24.1	17.2	24.2	12.8	103.12	48	0	7.8	14.8
22	19.8	25.2	17.3	102.58	75	1.02	10.2	22.2	17.6	24.2	13.1	102.78	57	0	6.5	11.1
23	19.7	24.2	14.4	102.12	75	0	3.7	9.4	19	29	11.8	102.36	51	0	4.8	7.6
24	20.9	25.4	14.9	101.95	69	0	6.9	14.8	20.9	31.9	15.2	102.26	37	0	8.3	14.8
25	22.2	29.6	14.9	101.51	57	0	4.3	13	18.8	31.9	13.8	101.71	38	0	6.3	13
26	22.4	29.6	19.8	101.84	75	0.51	7	11.1	22.9	31.3	17.1	101.3	42	0	10.7	20.6
27	21.4	25.2	17.8	101.65	78	0	6.9	13	19.4	31.3	18.1	102.38	75	6.1	7.8	16.5
28	21.2	25.4	15.9	100.97	70	0.25	5.4	9.4	19.6	22.2	17.5	102.7	73	0.25	8.5	18.3
29	22.6	26.6	18.3	101.37	70	0	8.1	13	19.1	24.1	15	102.18	79	0.25	7.4	14.8
30	22.4	28.9	16.4	101.5	66	0	8.7	22.2	19.5	24.1	14.4	102.17	71	0	7	11.1
31	21.6	28.9	18.7	101.65	72	0	12.4	27.8								
Monthly Ave	**21.3**	**26.3**	**17**	**101.8074**	**70.2**	**20.06**	**8.4**	**16.4**	**19.1**	**26**	**14.5**	**101.9387**	**57.4**	**7.62**	**8.6**	**14.9**

Table B4 Meteorological Data – July to August 2014

	July 2014								August 2014							
Day	**T_{ave} (ºC)**	**T_{max} (ºC)**	**T_{min} (ºC)**	**atm (kPa)**	**Humidity (%)**	**Rainfall (mm)**	**V_{ave} (km/h)**	**V_{max} (km/h)**	**T_{ave} (ºC)**	**T_{max} (ºC)**	**T_{min} (ºC)**	**atm (kPa)**	**Humidity (%)**	**Rainfall (mm)**	**V_{ave} (km/h)**	**V_{max} (km/h)**
1	19.9	25.5	15.1	102.12	68	0	8.3	20.6	20.8	26.9	16.3	102.19	62	0	7.4	13
2	18.7	25.5	13.4	102.15	67	0	7	16.5	21.1	24.2	17.3	102.17	77	0	12.4	22.2
3	18.6	24.4	13.3	101.89	60	0	5.2	11.1	19.1	24.5	15.5	101.95	80	0	7	14.8
4	19.2	24.4	13.3	101.44	52	0	7.8	18.3	18.6	24.5	14.4	101.54	65	0	5.9	9.4
5	20.3	29.8	13.8	101.05	56	0	10.9	18.3	21.1	28.2	14.2	101.53	66	0	10.2	18.3
6	15.2	29.8	14.1	102.25	63	1.02	9.8	11.1	21.3	28.2	18.3	101.97	72	0	7.4	11.1
7	14.4	17.5	12.3	102.75	63	2.03	11.1	14.8	21.6	24	18.4	102.47	77	0	10.6	18.3
8	14.7	18.4	12.1	103.01	49	0.51	12.6	16.5	21.7	24.2	18.6	102.65	75	0	7.2	11.1
9	15.1	23.1	10.4	102.99	42	0.25	11.9	14.8	21.6	27.7	17.2	102.05	66	0	8.3	22.2
10	16.3	23.1	11.4	103.2	51	0	13.1	16.5	22.1	27.7	19.3	102.37	63	0	10.6	20.6
11	16.3	22.1	11.3	102.57	58	0	11.9	14.8	21.5	26.4	17.7	102.39	73	0	11.9	24.1
12	17.4	23.8	9.7	101.95	36	0	14.3	20.6	21.3	25.6	17.5	102.1	71	0	12.6	22.2
13	-	-	-	-	-	-	-	-	20.2	25.4	14.9	101.72	76	0	8.5	16.5
14	18.3	22.9	14.1	102.85	57	0	11.3	18.3	20.7	25.3	15.5	102.02	61	0	12	22.2
15	18.2	22.9	14	102.62	70	0	12.8	18.3	19.6	25.3	17.1	102.73	64	0	8.3	13
16	18.6	24.7	13.2	101.82	61	0	14.6	24.1	19.1	22.7	17.1	103.15	82	2.03	6.1	7.6
17	19.2	26.3	13.5	100.78	48	0	15.7	25.9	20.1	22.2	18.1	102.57	72	0.25	12.4	24.1
18	21.3	26.3	16.8	101.21	62	0	12.8	16.5	19.2	23.8	13.8	101.52	76	0	8.3	16.5
19	19.6	25.3	16.1	101.89	61	0	12.8	16.5	24.6	33.6	15	101.14	42	0.25	6.5	11.1
20	18.2	25.3	14.7	102.7	64	0	11.7	14.8	21.3	33.6	19.4	101.56	77	0	6.9	11.1
21	19.6	23.6	15.8	102.82	68	0	11.7	13	20.6	24.2	18.5	101.21	78	0.25	8.3	16.5
22	18.1	23.4	15.4	102.23	72	0	4.4	13	19.7	22.5	16	101.51	51	6.1	11.3	18.3
23	19.7	24.5	15.5	102.04	60	0	0	-	19.7	22.9	12.5	101.41	51	0	11.1	13
24	18.9	24.5	15.5	101.73	73	0.25	7.2	16.5	20.5	24.1	13.3	101.81	48	0	17	27.8
25	19.1	23.9	13.1	101.01	64	0	7.2	11.1	18.4	24.1	14.2	102.06	57	0	8.9	16.5
26	19.6	23.9	17.3	101.7	60	0	9.6	16.5	19.5	23.6	13.1	101.85	68	0	7	16.5
27	18.3	23.6	14.6	102.57	56	0	8.9	13	21.7	27.4	15.4	101.01	67	0	11.3	22.2
28	18.8	23.7	14.7	103.26	56	0	13.9	24.1	21.2	27.4	17.7	100.85	61	0	8	11.1
29	18.3	24.3	14.2	103.1	61	0	15.4	29.4	17.3	23.6	13.9	101.77	34	0	16.1	22.2
30	18.1	25.5	12.4	102.44	58	0	5	7.6	19	23.2	16.1	102.7	42	0	16.1	24.1
31	18.9	26.9	12.6	101.99	45	0	8	13	19.7	23.3	16.5	102.93	55	0	16.9	24.1
Monthly Ave	**18.2**	**24.3**	**13.8**	**102.2043**	**58.7**	**4.06**	**10.2**	**16.7**	**20.4**	**25.5**	**16.2**	**101.9645**	**64.8**	**8.88**	**10.1**	**17.5**

Table B5 Meteorological Data – September 2014 to October 2014

	September 2014								October 2014							
Day	**T_{ave} (ºC)**	**T_{max} (ºC)**	**T_{min} (ºC)**	**atm (kPa)**	**Humidity (%)**	**Rainfall (mm)**	**V_{ave} (km/h)**	**V_{max} (km/h)**	**T_{ave} (ºC)**	**T_{max} (ºC)**	**T_{min} (ºC)**	**atm (kPa)**	**Humidity (%)**	**Rainfall (mm)**	**V_{ave} (km/h)**	**V_{max} (km/h)**
1	19.5	23.3	18	102.92	57	0	9.4	16.5	18.6	25.4	16.3	101.96	68	0	12.8	22.2
2	19.6	23.7	17.4	102.71	57	0	10.9	18.3	17.6	23.3	15.3	102.39	74	7.11	8.1	9.4
3	20	24.1	14.1	102.41	64	0	13.7	27.8	18.4	22.7	14.9	102.41	65	6.1	10.4	16.5
4	20	24.4	12.2	102.47	67	0	15.6	29.4	19.6	23.3	14.7	102.57	62	0	11.3	18.3
5	20.9	24.8	16.4	102.29	66	0	16.5	31.7	19.8	23.3	16.4	102.59	69	1.02	9.3	14.8
6	20.8	25.5	13.8	101.85	71	0	10.9	16.5	21.6	25.4	16.9	101.92	68	0.25	14.8	25.9
7	21.7	25.5	18	102.01	73	0	7.6	13	22.3	26.5	16.6	100.97	75	0	11.1	16.5
8	21.8	25.7	16.6	102.32	71	0	10.2	18.3	21.7	26.5	18.8	100.99	77	2.03	10.6	16.5
9	22.2	25.7	19.4	101.75	76	0	13.1	24.1	18.4	24.2	16.4	101.52	74	0.25	11.1	13
10	22.2	26.6	17.9	101.62	69	0	14.1	25.9	18.6	21.4	16	102.45	66	0.25	7.4	11.1
11	21.1	26.6	18	101.55	79	0.51	13.3	24.1	21.9	24.8	17.4	101.88	73	0.51	15.7	31.7
12	21.6	25.9	18.3	101.75	73	0.25	12.4	25.9	22.9	27	19.1	101.51	74	6.1	11.1	20.6
13	21.9	25.9	17.2	101.93	74	0	12	25.9	22	27	19.1	102.07	63	0.25	14.8	29.4
14	22.2	25.1	19.1	101.65	82	0	5.2	7.6	20.9	25.5	17.6	101.97	63	0.51	12	14.8
15	23.6	31	17.8	101.62	72	0	9.4	22.2	20.6	23.6	18.9	101.15	75	0	10	13
16	22.6	31	18.3	101.66	76	0	7	13	19	23.1	16.7	101.05	83	0.76	9.4	18.3
17	23.6	26.8	21.4	101.23	79	0.25	6.7	11.1	18.8	23.9	16.7	101.72	60	33.02	19.6	24.1
18	22.9	27.6	20.5	100.76	73	0	12	22.2	19.5	23.9	17.1	102.11	67	10.92	14.6	22.2
19	19.9	27.6	18.4	102.13	65	0.76	10.2	14.8	20.1	23.4	15.5	101.89	70	7.87	9.4	16.5
20	18.6	21.4	16.7	102.79	66	0.76	8.5	16.5	20.1	23.4	18	102.11	74	0	10.9	18.3
21	19.4	22.9	14.7	102.39	71	0	6.5	11.1	20.4	22.8	17.9	102.33	74	0.76	11.5	18.3
22	22	25.3	16.5	102.24	73	0	11.5	22.2	21.6	25.2	18.2	102.33	74	0.25	13.1	20.6
23	22.7	26.5	19.5	101.84	73	0	14.6	20.6	22.1	25.2	18.4	101.59	72	0.51	19.8	29.4
24	22.9	26.5	20.7	101.64	70	0	19.8	31.7	22.4	25.7	18	101.59	75	0.25	13.3	16.5
25	22.4	28.4	18.2	101.74	68	0	10.2	20.6	22.4	25.7	19.9	102	72	0	11.7	16.5
26	22.1	28.4	16.3	101.4	74	0	13.9	27.8	18.6	25.3	17.7	102.7	86	11.94	12.6	18.3
27	20.8	25.8	17.2	101.53	67	2.03	13.5	25.9	21.6	24.5	17.7	102.13	66	7.11	23.9	38.9
28	17.9	22.8	16.6	102.25	74	21.08	9.6	20.6	22.1	26.2	16.9	101.56	69	0.25	15.7	24.1
29	20.8	23.6	16.6	101.41	83	0	7.8	14.8	22.7	26.4	18.9	101.2	73	0	15.6	24.1
30	21.9	25.4	19.2	101.01	69	0.51	9.8	13	22.6	27.2	19.1	101.25	77	0	11.3	18.3
									20.9	27.2	17.8	101.98	75	0	9.6	11.1
Monthly Ave	**21.3**	**25.8**	**17.5**	**101.8957**	**71.1**	**26.15**	**11.2**	**20.4**	**20.6**	**24.8**	**17.4**	**101.8674**	**71.4**	**98.02**	**12.7**	**19.7**

Table B6 Meteorological Data – November to December 2014

November 2014									December 2014								
Day	**T_{ave} (ºC)**	**T_{max} (ºC)**	**T_{min} (ºC)**	**atm (kPa)**	**Humidity (%)**	**Rainfall (mm)**	**V_{ave} (km/h)**	**V_{max} (km/h)**	**Day**	**T_{ave} (ºC)**	**T_{max} (ºC)**	**T_{min} (ºC)**	**atm Pressure (kPa)**	**Humidity (%)**	**Rainfall (mm)**	**V_{ave} (km/h)**	**V_{max} (km/h)**
1	19.3	23.3	17.8	101.94	83	2.03	8.3	14.8	**1**	22.6	25.8	19.2	101.88	67	1.02	14.6	22.2
2	22.1	25.3	19.1	101.56	82	8.89	10.9	14.8	**2**	22.6	26.3	18.1	101.58	64	0.25	16.1	22.2
3	23.3	27.3	21.6	101.77	77	0	13.1	18.3	**3**	22.6	26.8	18	101.51	69	0	11.5	18.3
4	-	-	-		-	-	-	-	**4**	23.5	26.8	19.6	101.36	76	5.08	10.2	18.3
5	-	-	-		-	-	-	-	**5**	22.4	26.3	21.4	101.99	74	0.25	11.3	16.5
6	20.5	26.5	18.6	102.51	67	0.25	10	18.3	**6**	22.9	25.3	21.4	102.12	68	0	10.7	18.3
7	20.3	23.8	18.2	102.35	73	0.25	11.5	16.5	**7**	23.7	26.1	21.9	101.76	76	0	16.5	24.1
8	21.8	24.2	18	101.49	78	2.03	19.6	31.7	**8**	23.1	26.1	21.4	101.54	76	0.51	15.6	20.6
9	23.4	25.8	20.7	100.89	76	0	11.1	16.5	**9**	23.5	26.4	20.6	101.29	74	0	12.4	18.3
10	22.7	25.8	19.1	101.72	73	0.51	12.2	20.6	**10**	23.2	26.4	20.3	101.47	78	0	11.7	18.3
11	21.1	25.7	18.3	102.02	81	7.87	11.1	16.5	**11**	24.4	27.5	21.9	101.37	79	0.25	8.9	13
12	23.4	26.3	21.6	100.86	81	0	15.9	20.6	**12**	24.5	30	22.4	100.99	78	0	8.9	20.6
13	23.9	26.7	22.1	101.03	74	1.02	11.3	20.6	**13**	22.4	30	21.9	101.9	69	6.1	10.7	11.1
14	23.2	26.7	19.2	101.46	75	0.25	15.6	24.1	14	-	-	-	-	-	-	-	-
15	21.1	26	19.7	101.21	68	0	17.2	33.5	**15**	24.4	28.7	22.6	101.33	75	6.1	15	24.1
16	19.7	23.6	17.4	102.13	58	0	15.6	24.1	**16**	22.3	28.7	20.3	101.79	75	3.05	11.3	14.8
17	19.8	23.8	16.5	102.52	58	0.76	14.6	24.1	**17**	23.8	26.7	21.9	101.74	66	0	9.6	14.8
18	20.7	23.8	16.4	102.39	61	0	10	13	**18**	24.6	28.1	20.4	101.12	78	0.25	10.4	14.8
19	21.9	24.4	19.6	101.71	66	0.25	10.4	13	**19**	25.7	28.2	22.5	101.21	76	0	8.7	11.1
20	22.4	25.9	18.8	101.29	74	0	13.5	22.2	**20**	25.6	30	23	101.26	73	0	12.4	20.6
21	21	25.9	18.5	101.73	82	1.02	13	16.5	**21**	25.5	30	22.3	101.03	77	0.51	10.4	14.8
22	24.2	27.1	20.8	101.67	77	0	14.1	20.6	**22**	25.4	28.4	23.5	101.59	63	0.25	9.3	16.5
23	23.8	27.1	21.4	101.2	83	2.03	8.1	11.1	**23**	26.1	32	23	100.88	73	0	13	20.6
24	24.6	30.7	21.2	101.54	67	0	14.6	25.9	**24**	25.5	32	23.6	101.29	74	17.02	10.6	14.8
25	23.2	30.7	20.5	101.97	69	0	10.4	16.5	**25**	27.7	34	23.6	100.6	71	0	15.2	25.9
26	23.1	27	21.4	101.58	73	0	20.6	31.7	**26**	25.9	34	22.1	101.32	66	0	11.9	14.8
27	24.3	27.6	20.8	100.71	74	2.03	17.6	27.8	**27**	24.4	28.5	21.7	100.99	85	4.06	12	22.2
28	23.6	27.6	20.3	101.51	70	8.89	12	18.3	**28**	25.4	29.2	23.4	101.08	77	1.02	14.1	22.2
29	22.2	27	20.2	102.08	73	0.25	9.3	14.8	**29**	25.1	29.2	22.6	101.64	71	1.02	8.3	11.1
30	21.6	24.3	20.4	102.11	78	0	10.6	18.3	**30**	24	27.8	22	101.52	75	0.25	9.1	14.8
									31	-	-	-		-	-	-	-
Monthly Ave	**22.2**	**26.1**	**19.6**	**101.6768**	**73.3**	**38.33**	**12.9**	**20.2**	**Monthly Ave**	**24.2**	**28.5**	**21.6**	**101.419**	**73.2**	**46.99**	**11.7**	**17.9**

APPENDIX C

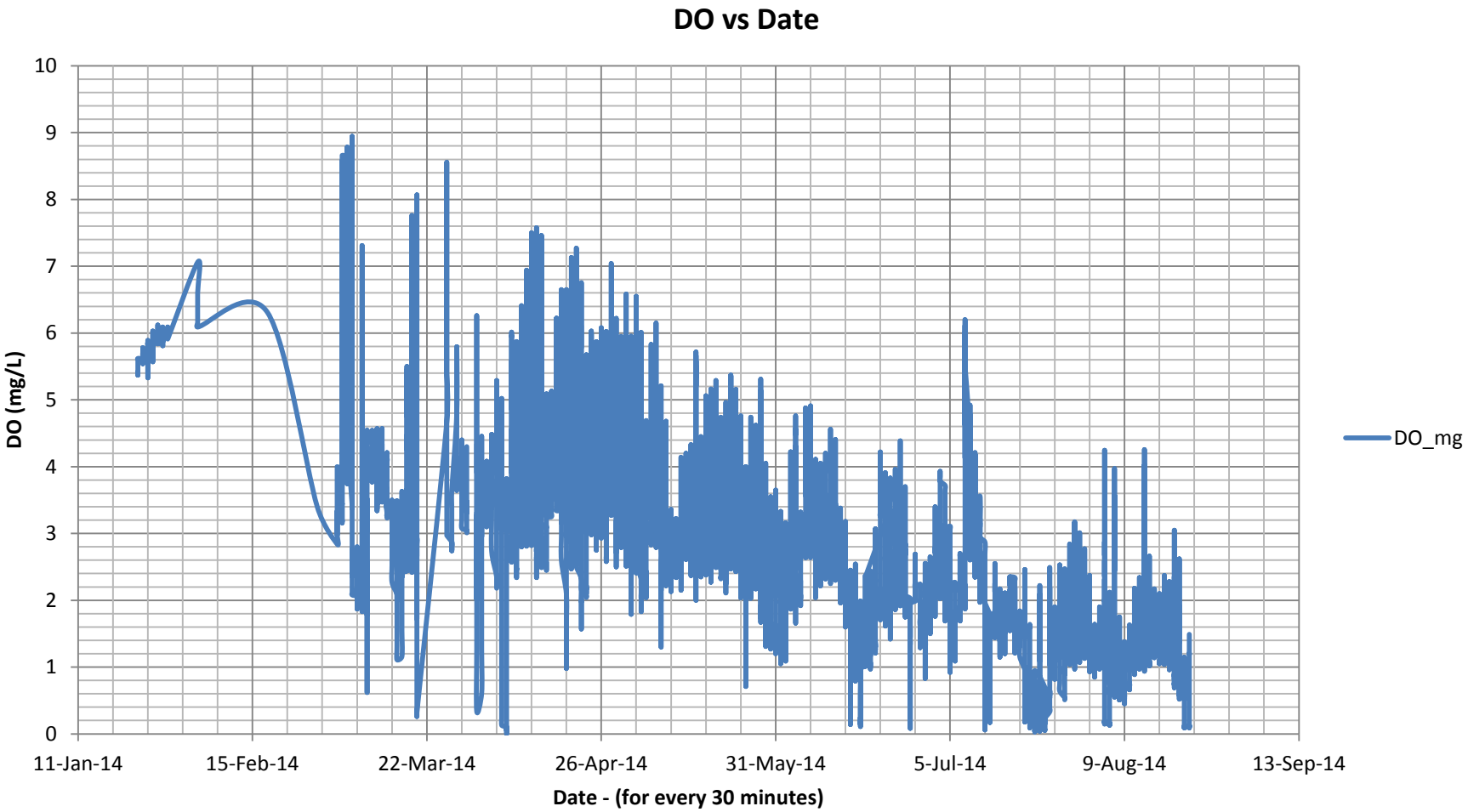

Figure C1 DO Data at Monitoring Station

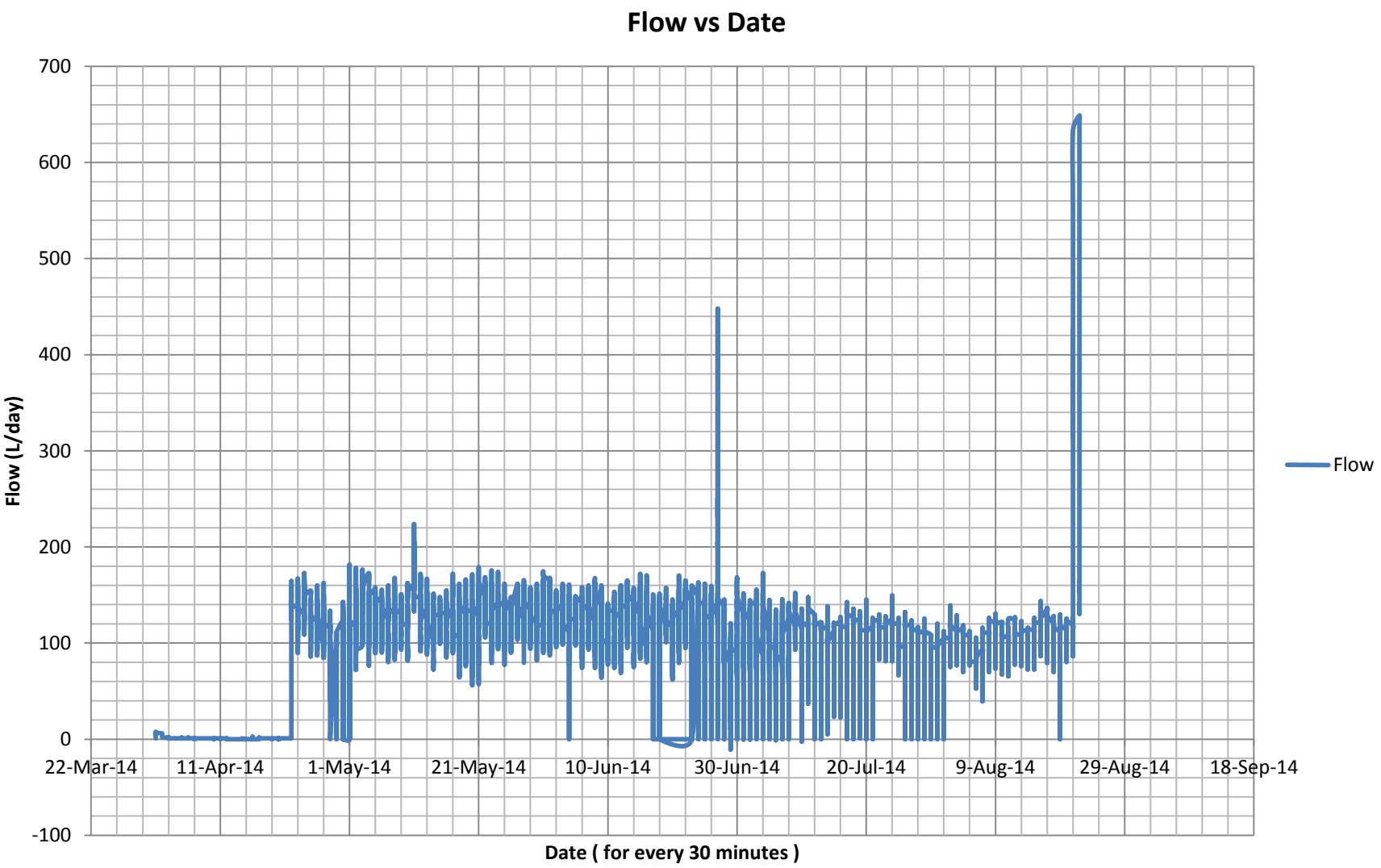

Figure C2 Flow Data at Monitoring Station

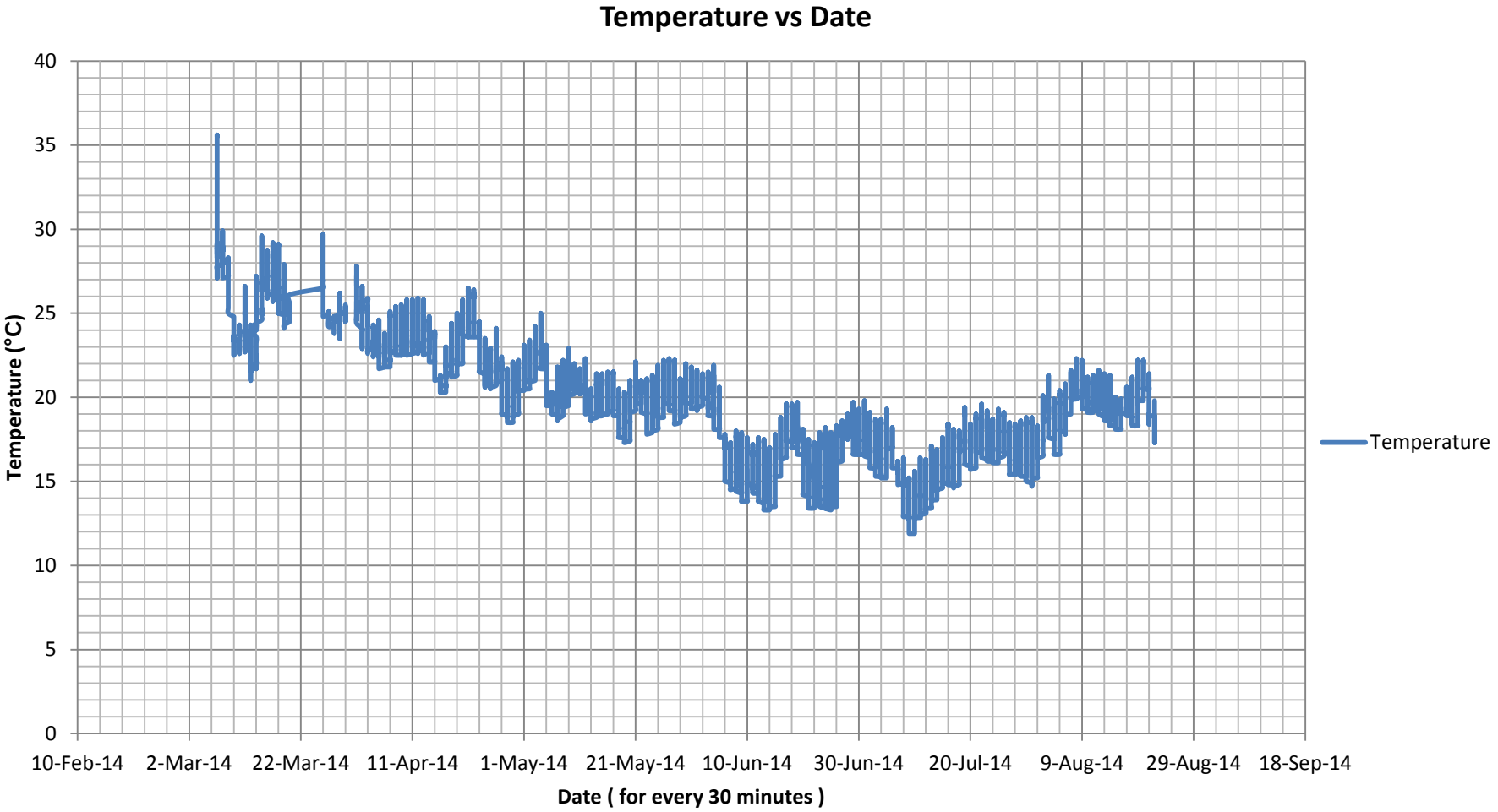

Figure C3 Temperature Data at Monitoring Station

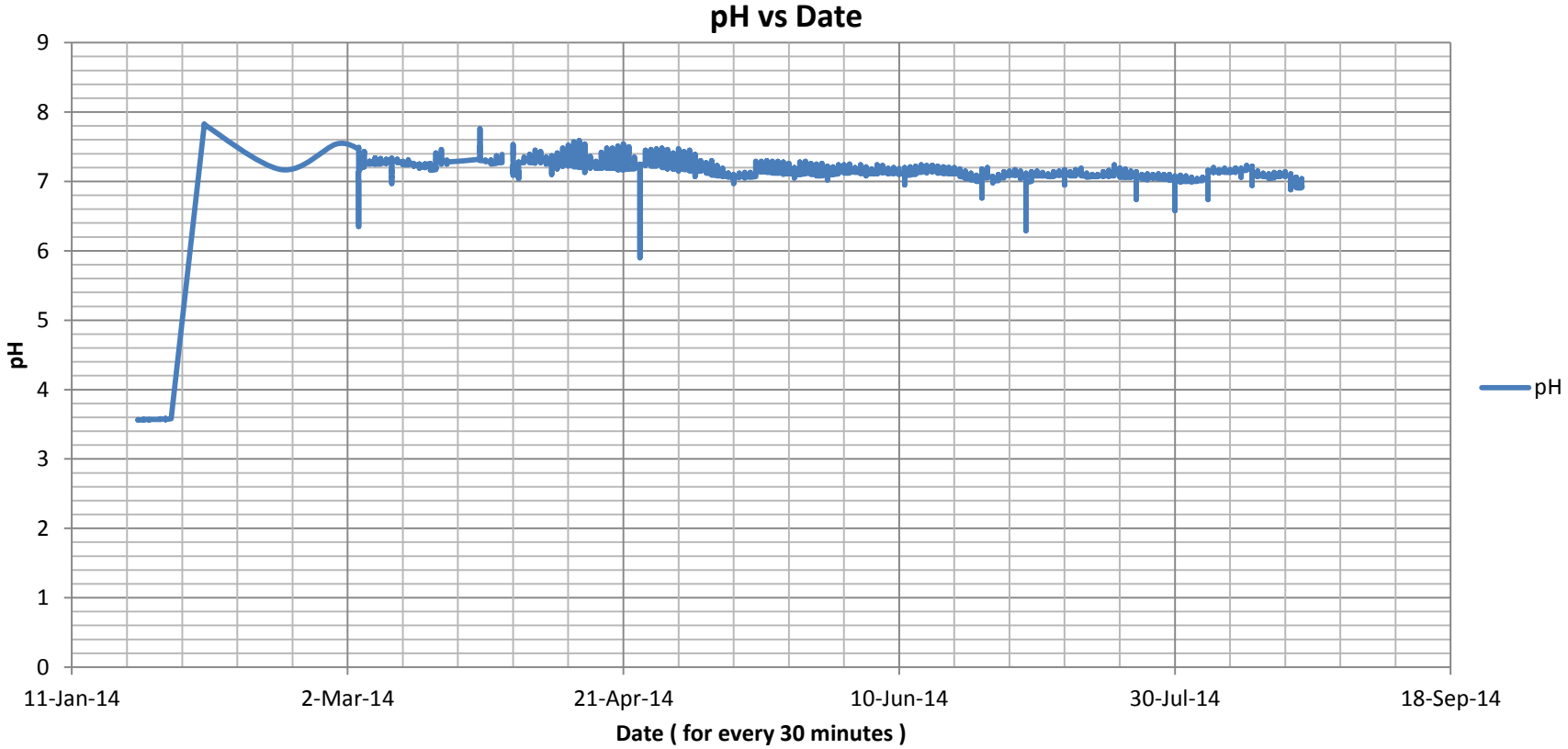

Figure C4 pH Data at Monitoring Station

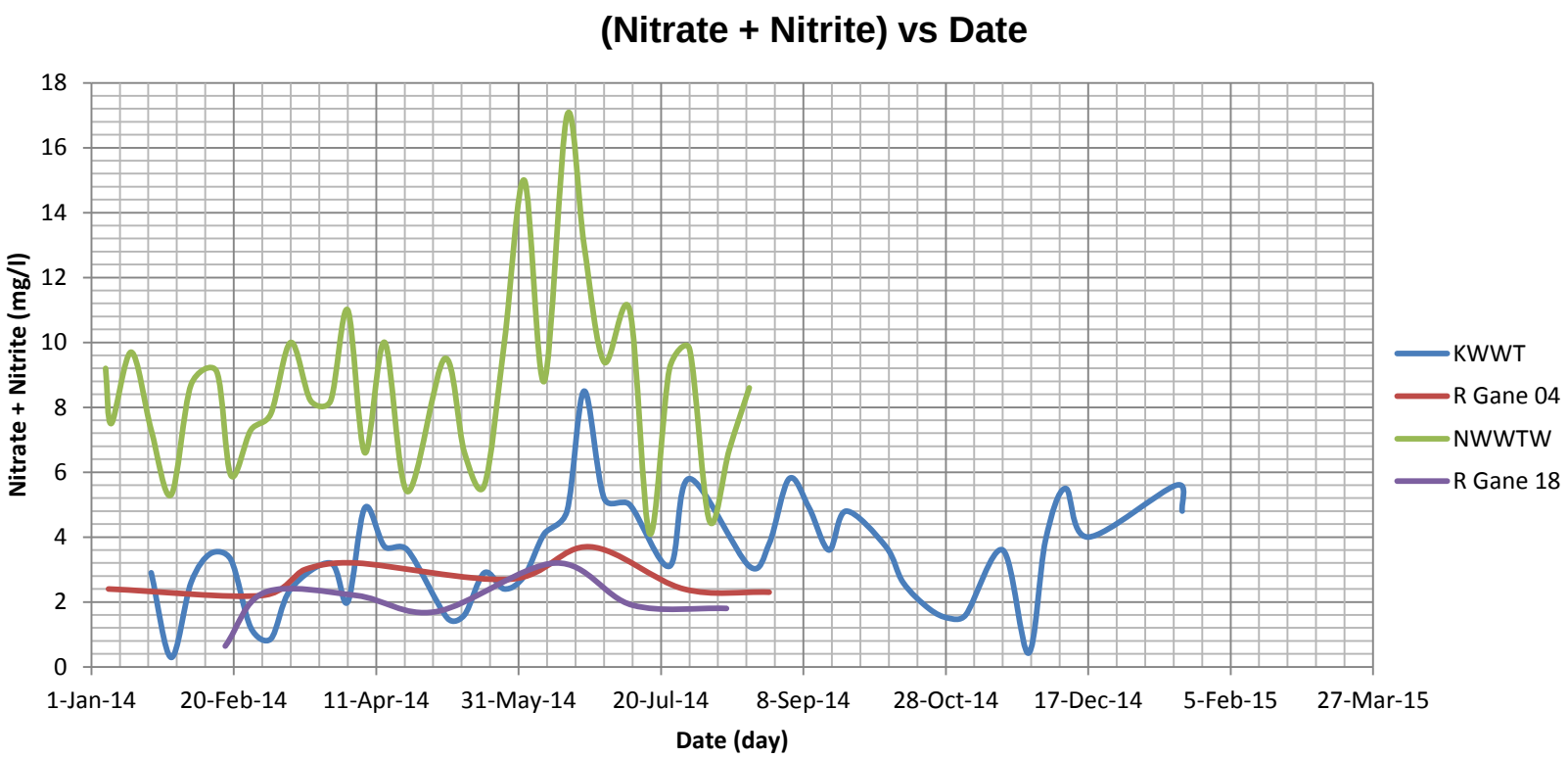

Figure C5 Variation of Ortho Phosphate concentration along Umhlangane River at various sampling points

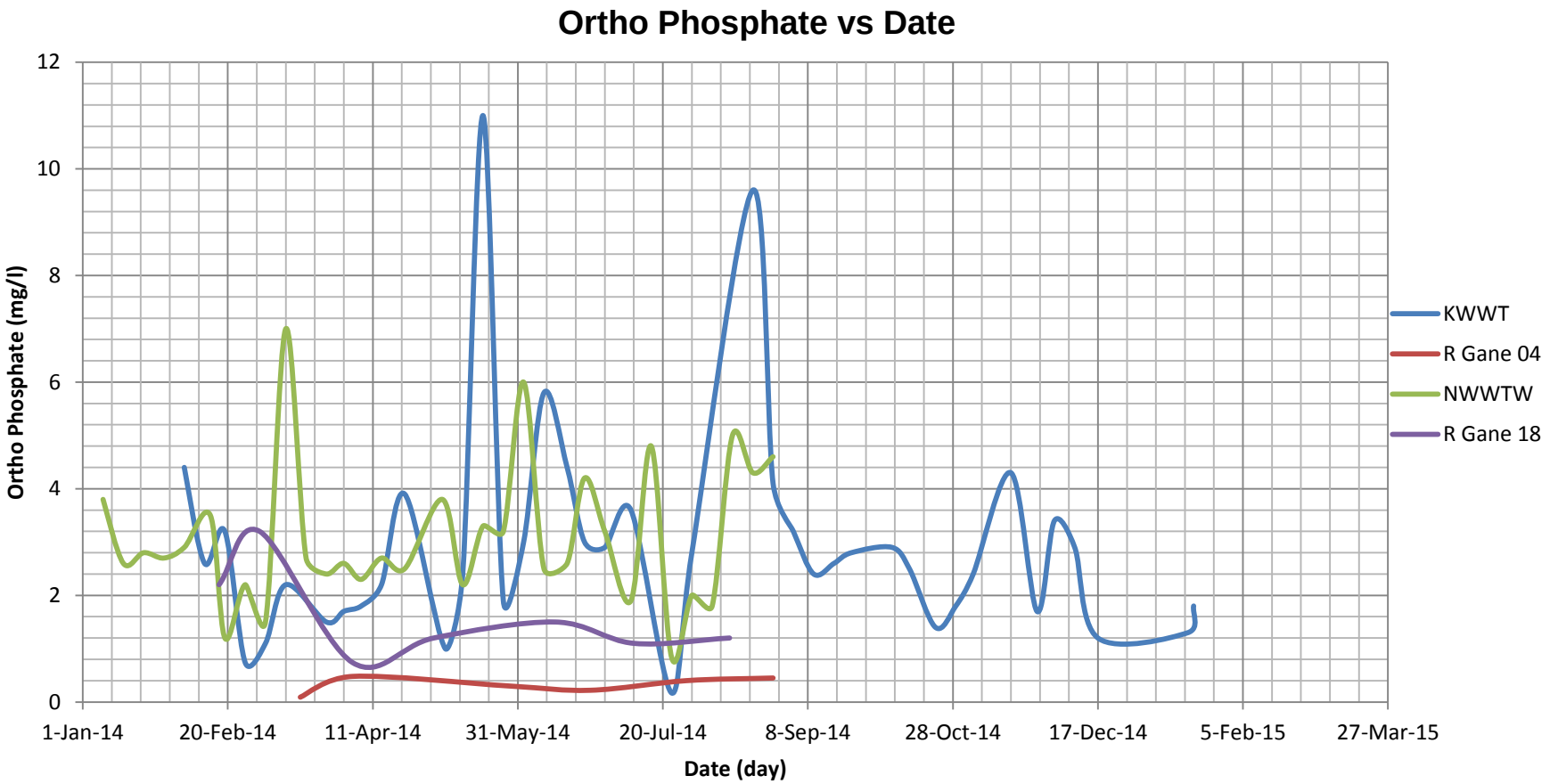

Figure C6 Variation of Ortho Phosphate concentration along Umhlangane River at various sampling points

Appendix D

Table D1 BOD & COD Simulation results, Observed data & RMS Error (R15 to R14)

Simulation results, Observed data & Root Mean Square Error (R15 to R14)						
	Observed Data	HECRAS	Observed Data	HECRAS	HEC-RAS (Resduals)	HEC-RAS (Resduals)
Date	COD	COD	BOD	BOD	COD	BOD
2014/01/22	53	53	26.5	26.500	0.000	0.000
2014/01/29	75	63.856	37.5	31.928	11.144	5.572
2014/02/05	44	58.566	22	29.283	-14.566	-7.283
2014/02/12	40	51.504	20	25.752	-11.504	-5.752
2014/02/19	66	52.682	33	26.341	13.318	6.659
2014/02/26	63	57.740	31.5	28.870	5.260	2.630
2014/03/05	59	61.010	29.5	30.505	-2.010	-1.005
2014/03/12	50	55.274	25	27.637	-5.274	-2.637
2014/03/26	52	53.138	26	26.569	-1.138	-0.569
2014/04/01	64	57.085	32	28.543	6.915	3.457
2014/04/07	64	58.297	32	29.148	5.703	2.852
2014/04/14	44	54.692	22	27.346	-10.692	-5.346
2014/04/22	49	48.005	24.5	24.002	0.995	0.498
2014/05/06	39	41.348	19.5	20.674	-2.348	-1.174
2014/05/12	45	42.078	22.5	21.039	2.922	1.461
2014/05/19	62	52.996	31	26.498	9.004	4.502
2014/05/26	38	51.801	19	25.900	-13.801	-6.900
2014/06/02	45	50.683	22.5	25.341	-5.683	-2.841
2014/06/09	79	63.581	39.5	31.790	15.419	7.710
2014/06/17	124	103.368	62	51.684	20.632	10.316
2014/06/23	77	98.988	38.5	49.494	-21.988	-10.994
2014/06/30	61	73.873	30.5	36.936	-12.873	-6.436
2014/07/09	65	63.675	32.5	31.838	1.325	0.662
2014/07/23	56	57.213	28	28.606	-1.213	-0.606
2014/07/30	56	55.989	28	27.995	0.011	0.005
2014/08/20	503	423.880	251.5	211.940	79.120	39.560
2014/09/03	50	87.069	25	43.535	-37.069	-18.535
2014/09/10	70	64.438	35	32.219	5.562	2.781
2014/09/17	71	68.765	35.5	34.382	2.235	1.118
2014/09/23	184	114.876	92	57.438	69.124	34.562
2014/10/07	52	91.046	26	45.523	-39.046	-19.523
2014/10/13	46	56.308	23	28.154	-10.308	-5.154
2014/10/22	53	50.751	26.5	25.375	2.249	1.125
2014/10/29	49	49.459	24.5	24.729	-0.459	-0.229
				RMSE	22.110	11.055

Table D2 BOD & COD Simulation results, Observed data & RMS Error (R14 to R13)

Simulation results, Observed data & Root Mean Square Error (R14 to R13)						
	Observed Data	HECRAS	Observed Data	HECRAS	HEC-RAS (Resduals)	HEC-RAS (Resduals)
Date	COD	COD	BOD	BOD	COD	BOD
2014-03-02	54	58.020	27	29.010	-4.020	-2.010
2014-03-17	34	56.880	17	28.440	-22.880	-11.440
2014-04-04	49	53.889	24.5	26.944	-4.889	-2.444
2014-05-28	29	50.503	14.5	25.252	-21.503	-10.752
2014-06-25	28	90.357	14	45.178	-62.357	-31.178
2014-07-28	36	61.181	18	30.591	-25.181	-12.591
				RMSE	30.409	15.205

Table D3 BOD & COD Simulation results, Observed data & RMS Error (R12.8 to R12.7)

Simulation results, Observed data & Root Mean Square Error (R12.8 to R12.7)						
	Observed Data	HECRAS	Observed Data	HECRAS	HEC-RAS (Residuals)	HEC-RAS (Residuals)
Date	COD (mg/L)	COD (mg/L)	BOD (mg/L)	BOD (mg/L)	COD	BOD
2014-02-17	70	62.204	35	31.102	7.796	3.898
2014-03-03	34	63.119	17	31.560	-29.119	-14.560
2014-04-04	50	56.310	25	28.155	-6.310	-3.155
2014-05-02	38	55.591	19	27.796	-17.591	-8.796
2014-06-13	28	49.814	14	24.907	-21.814	-10.907
2014-07-10	27	50.112	13.5	25.056	-23.112	-11.556
2014-08-12	29	70.422	14.5	35.211	-41.422	-20.711
				RMSE	23.856	11.928

Table D4 BOD & COD Simulation results, Observed data & RMS Error (R12.9 to R12.8)

Simulation results, Observed data & Root Mean Square Error (R12.9 to R12.8)						
Date	Observed Data COD	HECRAS COD	Observed Data BOD	HECRAS BOD	HEC-RAS (Resduals) COD	HEC-RAS (Resduals) BOD
2014-01-22	45	34.000	22.5	17.000	11.000	5.500
2014-01-29	79	65.128	39.5	32.564	13.872	6.936
2014-02-05	67	65.046	33.5	32.523	1.954	0.977
2014-02-14	82	64.857	41	32.428	17.143	8.572
2014-02-19	82	64.806	41	32.403	17.194	8.597
2014-02-26	71	63.509	35.5	31.755	7.491	3.745
2014-03-05	66	57.595	33	28.797	8.405	4.203
2014-03-12	84	55.888	42	27.944	28.112	14.056
2014-03-19	82	56.238	41	28.119	25.762	12.881
2014-03-26	71	56.285	35.5	28.143	14.715	7.357
2014-04-01	69	56.143	34.5	28.072	12.857	6.428
2014-04-07	66	55.869	33	27.934	10.131	5.066
2014-04-14	67	55.353	33.5	27.677	11.647	5.823
2014-04-22	71	55.564	35.5	27.782	15.436	7.718
2014-05-05	64	55.639	32	27.819	8.361	4.181
2014-05-12	59	55.609	29.5	27.805	3.391	1.695
2014-05-19	57	55.421	28.5	27.710	1.579	0.790
2014-05-26	46	52.697	23	26.348	-6.697	-3.348
2014-06-02	45	49.070	22.5	24.535	-4.070	-2.035
2014-06-09	58	49.050	29	24.525	8.950	4.475
2014-06-23	49	49.004	24.5	24.502	-0.004	-0.002
2014-06-30	41	48.980	20.5	24.490	-7.980	-3.990
2014-07-09	50	53.969	25	26.984	-3.969	-1.984
2014-07-16	84	63.728	42	31.864	20.272	10.136
2014-07-23	46	72.065	23	36.033	-26.065	-13.033
2014-07-30	46	72.020	23	36.010	-26.020	-13.010
2014-08-06	40	71.965	20	35.982	-31.965	-15.982
2014-08-13	58	68.351	29	34.176	-10.351	-5.176
2014-08-20	79	67.861	39.5	33.931	11.139	5.569
2014-08-27	66	67.829	33	33.915	-1.829	-0.915
				RMSE	14.916	7.458

Table D5 DO Simulation results, Observed data & RMS Error (R13 to R12.9)

Simulation results, Observed data & Root Mean Square Error (R13 to R12.9)					
Date	HEC-RAS (DO mg/L)	HCIS (DO mg/L)	Monitoring Station (DO mg/L)	HCIS Residual (DO)	HEC-RAS Residual (DO)
1/23/14 12:30 AM	5.500661	6.025174	5.61999989	-0.40517	0.119339
1/23/14 1:30 AM	5.450485	6.026353	5.59000015	-0.43635	0.139515
1/23/14 2:30 AM	5.401273	6.001226	5.57000017	-0.43123	0.168727
1/23/14 3:30 AM	5.353013	6.000049	5.53999996	-0.46005	0.186987
1/23/14 4:30 AM	5.305692	6.000002	5.53000021	-0.47	0.224308
1/23/14 5:30 AM	5.259296	6	5.5	-0.5	0.240704
1/23/14 6:30 AM	5.213815	6	5.48000002	-0.52	0.266185
1/23/14 7:30 AM	5.169234	6	5.44999981	-0.55	0.280766
1/23/14 8:30 AM	5.125543	6	5.44000006	-0.56	0.314457
1/23/14 9:30 AM	5.082728	6	5.42999983	-0.57	0.347272
1/23/14 10:30 AM	5.040778	6	5.40999985	-0.59	0.369222
1/23/14 11:30 AM	4.999681	6	5.38999987	-0.61	0.390319
1/23/14 12:30 PM	4.959425	6	5.4000001	-0.6	0.440575
1/23/14 1:30 PM	4.92	6	5.36999989	-0.63	0.45
1/23/14 2:30 PM	4.881392	6	5.4000001	-0.6	0.518608
1/23/14 3:30 PM	4.843592	6	5.38000011	-0.62	0.536408
1/23/14 4:30 PM	4.806587	5.999999	5.38999987	-0.61	0.583413
1/23/14 5:30 PM	4.770367	5.999982	5.38999987	-0.60998	0.619633
1/23/14 6:30 PM	4.734921	5.999848	5.4000001	-0.59985	0.665079
1/23/14 7:30 PM	4.700237	5.999311	5.40999985	-0.58931	0.709763
1/23/14 8:30 PM	4.666305	5.997943	5.42000008	-0.57794	0.753695
1/23/14 9:30 PM	4.633115	5.995353	5.69000006	-0.30535	1.056885
1/23/14 10:30 PM	4.600656	5.991301	5.67000008	-0.3213	1.069344
1/23/14 11:30 PM	4.568918	5.985701	5.65999985	-0.3257	1.091082
1/24/14 12:30 AM	4.53789	5.97857	5.63000011	-0.34857	1.09211
1/24/14 1:30 AM	4.507562	5.969981	5.5999999	-0.36998	1.092438
1/24/14 2:30 AM	4.477925	5.960033	5.59000015	-0.37003	1.112075
1/24/14 3:30 AM	4.448967	5.948839	5.57000017	-0.37884	1.121033
1/24/14 4:30 AM	4.420681	5.936511	5.55999994	-0.37651	1.139319
1/24/14 5:30 AM	4.393055	5.92316	5.55000019	-0.37316	1.156945
1/24/14 6:30 AM	4.366081	5.90889	5.57000017	-0.33889	1.203919
1/24/14 7:30 AM	4.339748	5.893801	5.57999992	-0.3138	1.240252
1/24/14 8:30 AM	4.314048	5.877984	5.61999989	-0.25798	1.305952
1/24/14 9:30 AM	4.28897	5.861527	5.67000008	-0.19153	1.38103
1/24/14 10:30 AM	4.264507	5.844512	5.73000002	-0.11451	1.465493
1/24/14 11:30 AM	4.240649	5.827012	5.78000021	-0.04701	1.539351
1/24/14 12:30 PM	4.217386	5.809098	5.75	-0.0591	1.532614
1/24/14 1:30 PM	4.194711	5.790834	5.71999979	-0.07083	1.525289
1/24/14 2:30 PM	4.172614	5.772283	5.71999979	-0.05228	1.547386
1/24/14 3:30 PM	4.151086	5.753498	5.69999981	-0.0535	1.548914
1/24/14 4:30 PM	4.13012	5.734532	5.69999981	-0.03453	1.56988
1/24/14 5:30 PM	4.109705	5.715432	5.71000004	-0.00543	1.600295
1/24/14 6:30 PM	4.089836	5.696244	5.69999981	0.003756	1.610164
1/24/14 7:30 PM	4.070501	5.677007	5.69000006	0.012993	1.619499

Simulation results, Observed data & Root Mean Square Error (R13 to R12.9)					
Date	**HEC-RAS (DO mg/L)**	**HCIS (DO mg/L)**	**Monitoring Station (DO mg/L)**	**HCIS Residual (DO)**	**HEC-RAS Residual (DO)**
1/24/14 8:30 PM	4.051695	5.657758	5.67000008	0.012242	1.618305
1/24/14 9:30 PM	4.033408	5.638533	5.6500001	0.011467	1.616592
1/24/14 10:30 PM	4.015633	5.619363	5.5999999	-0.01936	1.584367
1/24/14 11:30 PM	3.99836	5.600276	5.57000017	-0.03028	1.57164
1/25/14 12:30 AM	3.981584	5.5813	5.53999996	-0.0413	1.558416
1/25/14 1:30 AM	3.965296	5.562458	5.55999994	-0.00246	1.594704
1/25/14 2:30 AM	3.949487	5.543772	5.5999999	0.056228	1.650513
1/25/14 3:30 AM	3.934152	5.525261	5.67000008	0.144739	1.735848
1/25/14 4:30 AM	3.919281	5.506945	5.71999979	0.213055	1.800719
1/25/14 5:30 AM	3.904868	5.488838	5.75	0.261162	1.845132
1/25/14 6:30 AM	3.890905	5.470954	5.76999998	0.299046	1.879095
1/25/14 7:30 AM	3.877385	5.453309	5.76999998	0.316691	1.892615
1/25/14 8:30 AM	3.864301	5.435911	5.76999998	0.334089	1.905699
1/25/14 9:30 AM	3.851645	5.418771	5.76999998	0.351229	1.918355
1/25/14 10:30 AM	3.839411	5.401898	5.76000023	0.358102	1.920589
1/25/14 11:30 AM	3.827592	5.3853	5.75	0.3647	1.922408
1/25/14 12:30 PM	3.816181	5.368983	5.73000002	0.361017	1.913819
1/25/14 1:30 PM	3.80517	5.352952	5.73000002	0.377048	1.92483
1/25/14 2:30 PM	3.794554	5.337212	5.71999979	0.382788	1.925446
1/25/14 3:30 PM	3.784326	5.321767	5.69999981	0.378233	1.915674
1/25/14 4:30 PM	3.774479	5.306619	5.69000006	0.383381	1.915521
1/25/14 5:30 PM	3.765007	5.29177	5.67000008	0.37823	1.904993
1/25/14 6:30 PM	3.755903	5.277223	5.65999985	0.382777	1.904097
1/25/14 7:30 PM	3.747161	5.262977	5.6500001	0.387023	1.902839
1/25/14 8:30 PM	3.738774	5.249032	5.63999987	0.390968	1.901226
1/25/14 9:30 PM	3.730738	5.23539	5.61999989	0.38461	1.889262
1/25/14 10:30 PM	3.723045	5.222047	5.8499999	0.627953	2.126955
1/25/14 11:30 PM	3.715689	5.209004	5.82000017	0.610996	2.104311
1/26/14 12:30 AM	3.708665	5.196258	5.78999996	0.593742	2.081335
1/26/14 1:30 AM	3.701967	5.183807	5.76999998	0.586193	2.068033
1/26/14 2:30 AM	3.695589	5.171649	5.71999979	0.548351	2.024411
1/26/14 3:30 AM	3.689525	5.159781	5.69000006	0.530219	2.000475
1/26/14 4:30 AM	3.683769	5.148201	5.63999987	0.491799	1.956231
1/26/14 5:30 AM	3.678316	5.136904	5.59000015	0.453096	1.911684
1/26/14 6:30 AM	3.67316	5.125887	5.55999994	0.434113	1.88684
1/26/14 7:30 AM	3.668296	5.115147	5.53000021	0.414853	1.861704
1/26/14 8:30 AM	3.663718	5.104679	5.48999977	0.385321	1.826282
1/26/14 9:30 AM	3.659421	5.09448	5.46999979	0.37552	1.810579
1/26/14 10:30 AM	3.655401	5.084545	5.46000004	0.375455	1.804599
1/26/14 11:30 AM	3.65165	5.074871	5.40999985	0.335129	1.75835
1/26/14 12:30 PM	3.648136	5.065452	5.38000011	0.314548	1.731864
1/26/14 1:30 PM	3.644854	5.056283	5.36999989	0.313717	1.725146
1/26/14 2:30 PM	3.641799	5.047362	5.34000015	0.292638	1.698201
1/26/14 3:30 PM	3.638967	5.038683	5.32999992	0.291317	1.691033
1/26/14 4:30 PM	3.636353	5.030241	5.32999992	0.299759	1.693647
1/26/14 5:30 PM	3.633953	5.022031	5.32999992	0.307969	1.696047
1/26/14 6:30 PM	3.631763	5.01405	5.34000015	0.32595	1.708237
1/26/14 7:30 PM	3.629777	5.006291	5.36000013	0.353709	1.730223
1/26/14 8:30 PM	3.627993	4.998752	5.38999987	0.391248	1.762007
1/26/14 9:30 PM	3.626406	4.991426	5.42000008	0.428574	1.793594
1/26/14 10:30 PM	3.625012	4.984308	5.44000006	0.455692	1.814988
1/26/14 11:30 PM	3.623807	4.977396	5.44000006	0.462604	1.816193
1/27/14 12:30 AM	3.622787	4.970682	5.46000004	0.489318	1.837213
1/27/14 1:30 AM	3.621947	4.964164	5.48999977	0.525836	1.868053
1/27/14 2:30 AM	3.621284	4.957836	5.53000021	0.572164	1.908716
1/27/14 3:30 AM	3.620795	4.951694	5.5999999	0.648306	1.979205
1/27/14 4:30 AM	3.620475	4.945734	5.67999983	0.734266	2.059525
1/27/14 5:30 AM	3.62032	4.939951	5.78000021	0.840049	2.15968
1/27/14 6:30 AM	3.620327	4.93434	5.8499999	0.91566	2.229673
1/27/14 7:30 AM	3.620491	4.928897	5.88999987	0.961103	2.269509
1/27/14 8:30 AM	3.620808	4.923618	5.88000011	0.956382	2.259192
1/27/14 9:30 AM	3.621276	4.918499	5.88000011	0.961501	2.258724
1/27/14 10:30 AM	3.621891	4.913536	5.86999989	0.956464	2.248109
1/27/14 11:30 AM	3.622648	4.908724	5.8499999	0.941276	2.227352
1/27/14 12:30 PM	3.623544	4.90406	5.84000015	0.93594	2.216456
1/27/14 1:30 PM	3.624577	4.899539	5.82999992	0.930461	2.205423
1/27/14 2:30 PM	3.625741	4.895159	5.82000017	0.924841	2.194259
1/27/14 3:30 PM	3.627035	4.890913	5.80000019	0.909087	2.172965
1/27/14 4:30 PM	3.628454	4.886801	5.78000021	0.893199	2.151546
1/27/14 5:30 PM	3.629996	4.882816	5.76000023	0.877184	2.130004
1/27/14 6:30 PM	3.631656	4.878957	5.75	0.871043	2.118344
1/27/14 7:30 PM	3.633433	4.87522	5.73999977	0.86478	2.106567
1/27/14 8:30 PM	3.635323	4.8716	5.73000002	0.8584	2.094677
1/27/14 9:30 PM	3.637323	4.868095	5.71000004	0.841905	2.072677
1/27/14 10:30 PM	3.63943	4.864702	5.9000001	1.035298	2.26057
1/27/14 11:30 PM	3.64164	4.861417	5.86000013	0.998583	2.21836
1/28/14 12:30 AM	3.643952	4.858237	5.82999992	0.971763	2.186048
1/28/14 1:30 AM	3.646361	4.855159	5.82000017	0.964841	2.173639
1/28/14 2:30 AM	3.648867	4.85218	5.76999998	0.91782	2.121133
1/28/14 3:30 AM	3.651465	4.849298	5.73999977	0.890702	2.088535
1/28/14 4:30 AM	3.654153	4.846509	5.71999979	0.873491	2.065847
1/28/14 5:30 AM	3.656929	4.84381	5.69000006	0.84619	2.033071
1/28/14 6:30 AM	3.65979	4.841199	5.65999985	0.818801	2.00021
1/28/14 7:30 AM	3.662733	4.838674	5.63999987	0.801326	1.977267
1/28/14 8:30 AM	3.665756	4.83623	5.61000013	0.77377	1.944244
1/28/14 9:30 AM	3.668856	4.833868	5.5999999	0.766132	1.931144
1/28/14 10:30 AM	3.672032	4.831583	5.59000015	0.758417	1.917968
1/28/14 11:30 AM	3.675281	4.829373	5.57000017	0.740627	1.894719
1/28/14 12:30 PM	3.6786	4.827237	5.57000017	0.742763	1.8914
1/28/14 1:30 PM	3.681987	4.825171	5.57000017	0.744829	1.888013

Simulation results, Observed data & Root Mean Square Error (R13 to R12.9)					
Date	**HEC-RAS (DO mg/L)**	**HCIS (DO mg/L)**	**Monitoring Station (DO mg/L)**	**HCIS Residual (DO)**	**HEC-RAS Residual (DO)**
1/28/14 2:30 PM	3.68544	4.823174	5.59000015	0.766826	1.90456
1/28/14 3:30 PM	3.688957	4.821243	5.5999999	0.778757	1.911043
1/28/14 4:30 PM	3.692535	4.819377	5.59000015	0.770623	1.897465
1/28/14 5:30 PM	3.696173	4.817573	5.61999989	0.802427	1.923827
1/28/14 6:30 PM	3.699869	4.815829	5.63000011	0.814171	1.930131
1/28/14 7:30 PM	3.703619	4.814145	5.65999985	0.845855	1.956381
1/28/14 8:30 PM	3.707423	4.812516	5.67000008	0.857484	1.962577
1/28/14 9:30 PM	3.711279	4.810943	5.71000004	0.899057	1.998721
1/28/14 10:30 PM	3.715184	4.809423	5.73000002	0.920577	2.014816
1/28/14 11:30 PM	3.719136	4.807954	5.75	0.942046	2.030864
1/29/14 12:30 AM	3.723135	4.806535	5.78999996	0.983465	2.066865
1/29/14 1:30 AM	3.727177	4.805164	5.84000015	1.034836	2.112823
1/29/14 2:30 AM	3.731261	4.80384	5.88000011	1.07616	2.148739
1/29/14 3:30 AM	3.735386	4.802561	5.90999985	1.107439	2.174614
1/29/14 4:30 AM	3.739549	4.801326	5.94000006	1.138674	2.200451
1/29/14 5:30 AM	3.74375	4.800133	5.96000004	1.159867	2.21625
1/29/14 6:30 AM	3.747986	4.798981	6	1.201019	2.252014
1/29/14 7:30 AM	3.752256	4.797868	6.01000023	1.212132	2.257744
1/29/14 8:30 AM	3.756558	4.796794	6.03000021	1.233206	2.273442
1/29/14 9:30 AM	3.760891	4.795756	6.01000023	1.214244	2.249109
1/29/14 10:30 AM	3.765253	4.794755	5.98999977	1.195245	2.224747
1/29/14 11:30 AM	3.769643	4.793788	5.98999977	1.196212	2.220357
1/29/14 12:30 PM	3.77406	4.792854	5.98000002	1.187146	2.20594
1/29/14 1:30 PM	3.778501	4.791953	5.96000004	1.168047	2.181499
1/29/14 2:30 PM	3.782965	4.791083	5.96000004	1.168917	2.177035
1/29/14 3:30 PM	3.787452	4.790244	5.94999981	1.159756	2.162548
1/29/14 4:30 PM	3.79196	4.789433	5.94000006	1.150567	2.14804
1/29/14 5:30 PM	3.796487	4.788651	5.92000008	1.131349	2.123513
1/29/14 6:30 PM	3.801032	4.787896	5.90999985	1.122104	2.108968
1/29/14 7:30 PM	3.805594	4.787168	5.9000001	1.112832	2.094406
1/29/14 8:30 PM	3.810172	4.786465	5.88000011	1.093535	2.069828
1/29/14 9:30 PM	3.814764	4.785787	5.86999989	1.084213	2.055236
1/29/14 10:30 PM	3.819369	4.785132	5.98000002	1.194868	2.160631
1/29/14 11:30 PM	3.823987	4.784501	5.96999979	1.185499	2.146013
1/30/14 12:30 AM	3.828615	4.783892	5.94999981	1.166108	2.121385
1/30/14 1:30 AM	3.833253	4.783304	5.94000006	1.156696	2.106747
1/30/14 2:30 AM	3.837899	4.782736	5.92999983	1.147264	2.092101
1/30/14 3:30 AM	3.842553	4.782189	5.94000006	1.157811	2.097447
1/30/14 4:30 AM	3.847214	4.781662	5.90999985	1.128338	2.062786
1/30/14 5:30 AM	3.851879	4.781153	5.90999985	1.128847	2.058121
1/30/14 6:30 AM	3.856548	4.780662	5.9000001	1.119338	2.043452
1/30/14 7:30 AM	3.86122	4.780188	5.9000001	1.119812	2.03878
1/30/14 8:30 AM	3.865895	4.779731	5.9000001	1.120269	2.034105
1/30/14 9:30 AM	3.87057	4.779291	5.88999987	1.110709	2.01943
1/30/14 10:30 AM	3.875246	4.778866	5.86999989	1.091134	1.994754
1/30/14 11:30 AM	3.87992	4.778456	5.86000013	1.081544	1.98008
1/30/14 12:30 PM	3.884593	4.778061	5.86000013	1.081939	1.975407
1/30/14 1:30 PM	3.889263	4.77768	5.8499999	1.07232	1.960737
1/30/14 2:30 PM	3.893924	4.777313	5.84000015	1.062687	1.946076
1/30/14 3:30 PM	3.898575	4.776958	5.8499999	1.073042	1.951425
1/30/14 4:30 PM	3.903215	4.776617	5.84000015	1.063383	1.936785
1/30/14 5:30 PM	3.907844	4.776288	5.86000013	1.083712	1.952156
1/30/14 6:30 PM	3.912461	4.77597	5.8499999	1.07403	1.937539
1/30/14 7:30 PM	3.917065	4.775664	5.8499999	1.074336	1.932935
1/30/14 8:30 PM	3.921655	4.775369	5.86999989	1.094631	1.948345
1/30/14 9:30 PM	3.926232	4.775085	5.88000011	1.104915	1.953768
1/30/14 10:30 PM	3.930794	4.774811	5.9000001	1.125189	1.969206
1/30/14 11:30 PM	3.93534	4.774547	5.9000001	1.125453	1.96466
1/31/14 12:30 AM	3.939871	4.774292	5.9000001	1.125708	1.960129
1/31/14 1:30 AM	3.944385	4.774046	5.92999983	1.155954	1.985615
1/31/14 2:30 AM	3.948882	4.773809	5.92999983	1.156191	1.981118
1/31/14 3:30 AM	3.953361	4.773582	5.96000004	1.186418	2.006639
1/31/14 4:30 AM	3.957822	4.773362	5.98000002	1.206638	2.022178
1/31/14 5:30 AM	3.962265	4.77315	6.03000021	1.25685	2.067735
1/31/14 6:30 AM	3.966688	4.772945	6.07000017	1.297055	2.103312
1/31/14 7:30 AM	3.971092	4.772749	6.11000013	1.337251	2.138908
1/31/14 8:30 AM	3.975475	4.772559	6.11999989	1.347441	2.144525
1/31/14 9:30 AM	3.979838	4.772377	6.11000013	1.337623	2.130162
1/31/14 10:30 AM	3.984179	4.772201	6.0999999	1.327799	2.115821
1/31/14 11:30 AM	3.988499	4.772031	6.07000017	1.297969	2.081501
1/31/14 12:30 PM	3.992797	4.771868	6.07000017	1.298132	2.077203
1/31/14 1:30 PM	3.997072	4.77171	6.05999994	1.28829	2.062928
1/31/14 2:30 PM	4.001324	4.771558	6.05999994	1.288442	2.058676
1/31/14 3:30 PM	4.005553	4.771412	6.03999996	1.268588	2.034447
1/31/14 4:30 PM	4.009758	4.771272	6.01000023	1.238728	2.000242
1/31/14 5:30 PM	4.013938	4.771136	6.01000023	1.238864	1.996062
1/31/14 6:30 PM	4.018095	4.771005	5.96999979	1.198995	1.951905
1/31/14 7:30 PM	4.022226	4.770879	5.96000004	1.189121	1.937774
1/31/14 8:30 PM	4.026332	4.770758	5.94000006	1.169242	1.913668
1/31/14 9:30 PM	4.030412	4.770641	5.90999985	1.139359	1.879588
1/31/14 10:30 PM	4.034467	4.770529	5.96999979	1.199471	1.935533
1/31/14 11:30 PM	4.038495	4.77042	5.94999981	1.17958	1.911505
2/1/14 12:30 AM	4.042496	4.770316	5.94999981	1.179684	1.907504
2/1/14 1:30 AM	4.046471	4.770215	5.94999981	1.179785	1.903529
2/1/14 2:30 AM	4.050418	4.770119	5.94000006	1.169881	1.889582
2/1/14 3:30 AM	4.054338	4.770025	5.94000006	1.169975	1.885662
2/1/14 4:30 AM	4.058229	4.769935	5.92000008	1.150065	1.861771
2/1/14 5:30 AM	4.062093	4.769849	5.9000001	1.130151	1.837907
2/1/14 6:30 AM	4.065928	4.769765	5.9000001	1.130235	1.834072
2/1/14 7:30 AM	4.069735	4.769685	5.88999987	1.120315	1.820265

Simulation results, Observed data & Root Mean Square Error (R13 to R12.9)					
Date	**HEC-RAS (DO mg/L)**	**HCIS (DO mg/L)**	**Monitoring Station (DO mg/L)**	**HCIS Residual (DO)**	**HEC-RAS Residual (DO)**
2/1/14 8:30 AM	4.073513	4.769608	5.88999987	1.120392	1.816487
2/1/14 9:30 AM	4.077262	4.769533	5.88999987	1.120467	1.812738
2/1/14 10:30 AM	4.080981	4.769462	5.88000011	1.110538	1.799019
2/1/14 11:30 AM	4.084671	4.769393	5.86000013	1.090607	1.775329
2/1/14 12:30 PM	4.088331	4.769326	5.86000013	1.090674	1.771669
2/1/14 1:30 PM	4.091962	4.769262	5.82999992	1.060738	1.738038
2/1/14 2:30 PM	4.095562	4.769201	5.82000017	1.050799	1.724438
2/1/14 3:30 PM	4.099132	4.769141	5.80999994	1.040859	1.710868
2/1/14 4:30 PM	4.102671	4.769084	5.82000017	1.050916	1.717329
2/1/14 5:30 PM	4.10618	4.769029	5.82000017	1.050971	1.71382
2/1/14 6:00 PM	4.109657	4.768976	5.82999992	1.061024	1.720343
2/1/14 7:00 PM	4.113104	4.768925	5.8499999	1.081075	1.736896
2/1/14 8:00 PM	4.11652	4.768876	5.9000001	1.131124	1.78348
2/1/14 9:00 PM	4.119904	4.768829	5.86999989	1.101171	1.750096
2/1/14 10:00 PM	4.123257	4.768784	5.92000008	1.151216	1.796743
2/1/14 11:00 PM	4.126578	4.76874	5.94000006	1.17126	1.813422
2/2/14 12:00 AM	4.129867	4.768698	5.96999979	1.201302	1.840133
2/2/14 1:00 AM	4.13312	4.768657	5.96000004	1.191343	1.82688
2/2/14 2:00 AM	4.136338	4.768618	5.98000002	1.211382	1.843662
2/2/14 3:00 AM	4.13952	4.76858	6.01000023	1.24142	1.87048
2/2/14 4:00 AM	4.142666	4.768544	6.03000021	1.261456	1.887334
2/2/14 5:00 AM	4.145777	4.768509	6.05000019	1.281491	1.904223
2/2/14 6:00 AM	4.148852	4.768476	6.07999992	1.311524	1.931148
2/2/14 7:00 AM	4.151892	4.768444	6.07999992	1.311556	1.928108
2/2/14 8:00 AM	4.154895	4.768413	6.09000015	1.321587	1.935105
2/2/14 9:00 AM	4.157864	4.768383	6.07000017	1.301617	1.912136
2/2/14 10:00 AM	4.160796	4.768354	6.07999992	1.311646	1.919204
2/2/14 11:00 AM	4.163693	4.768326	6.05999994	1.291674	1.896307
2/2/14 12:00 PM	4.166555	4.7683	6.05000019	1.2817	1.883445
2/2/14 1:00 PM	4.169382	4.768274	6.05000019	1.281726	1.880618
2/2/14 2:00 PM	4.172173	4.768249	6.03000021	1.261751	1.857827
2/2/14 3:00 PM	4.174928	4.768225	6.03000021	1.261775	1.855072
2/2/14 4:00 PM	4.177649	4.768202	6.01999998	1.251798	1.842351
2/2/14 5:00 PM	4.180335	4.76818	6.01000023	1.24182	1.829665
2/2/14 6:00 PM	4.182985	4.768159	6	1.231841	1.817015
2/2/14 7:00 PM	4.185601	4.768139	6	1.231861	1.814399
2/2/14 8:00 PM	4.188182	4.768119	5.98999977	1.221881	1.801818
2/2/14 9:00 PM	4.190729	4.7681	5.96999979	1.2019	1.779271
2/2/14 10:00 PM	4.193241	4.768082	5.90999985	1.141918	1.716759
2/2/14 11:00 PM	4.195718	4.768064	5.94000006	1.171936	1.744282
2/3/14 12:00 AM	4.198161	4.768048	5.96999979	1.201952	1.771839
2/3/14 1:00 AM	4.20057	4.768032	6	1.231968	1.79943
2/3/14 2:00 AM	4.202944	4.768016	6.05000019	1.281984	1.847056
2/3/14 3:00 AM	4.205284	4.768002	6.07000017	1.301998	1.864716
2/3/14 4:00 AM	4.20759	4.767987	6.09000015	1.322013	1.88241
2/3/14 5:00 AM	4.20986	4.767973	6.07000017	1.302027	1.86014
2/3/14 6:00 AM	4.212097	4.76796	6.07000017	1.30204	1.857903
2/3/14 7:00 AM	4.214299	4.767947	6.05999994	1.292053	1.845701
2/3/14 8:00 AM	4.216467	4.767935	6.03999996	1.272065	1.823533
2/3/14 9:00 AM	4.218601	4.767922	6.03000021	1.262078	1.811399
2/3/14 10:00 AM	4.2207	4.767911	6.03000021	1.262089	1.8093
2/3/14 11:00 AM	4.222765	4.7679	6.01000023	1.2421	1.787235
2/3/14 12:00 PM	4.224797	4.767889	5.98999977	1.222111	1.765203
2/3/14 1:00 PM	4.226793	4.767879	5.98000002	1.212121	1.753207
2/3/14 2:00 PM	4.228756	4.76787	5.98999977	1.22213	1.761244
2/3/14 3:00 PM	4.230685	4.76786	5.98000002	1.21214	1.749315
2/3/14 4:00 PM	4.23258	4.767851	5.96999979	1.202149	1.73742
2/3/14 5:00 PM	4.234441	4.767843	5.96000004	1.192157	1.725559
2/3/14 6:00 PM	4.236268	4.767834	6.09000015	1.322166	1.853732
2/3/14 7:00 PM	4.238061	4.767826	6.1500001	1.382174	1.911939
2/3/14 8:00 PM	4.239821	4.767818	6.17999983	1.412182	1.940179
2/3/14 9:00 PM	4.241547	4.767811	6.32000017	1.552189	2.078453
2/3/14 10:00 PM	4.24324	4.767804	6.5999999	1.832196	2.35676
2/3/14 11:00 PM	4.244899	4.767797	7.05999994	2.292203	2.815101
2/4/14 12:00 AM	4.246524	4.76779	6.30999994	1.54221	2.063476
2/4/14 1:00 AM	4.248117	4.767784	3.4000001	-1.36778	-0.84812
2/4/14 2:00 AM	4.249677	4.767777	4	-0.76778	-0.24968
2/4/14 3:00 AM	4.251203	4.767772	3.99000001	-0.77777	-0.2612
2/4/14 4:00 AM	4.252697	4.767766	3.8599999	-0.90777	-0.3927
2/4/14 5:00 AM	4.254158	4.76776	3.73000002	-1.03776	-0.52416
2/4/14 6:00 AM	4.255586	4.767755	3.6099999	-1.15776	-0.64559
2/4/14 7:00 AM	4.256982	4.76775	3.48000002	-1.28775	-0.77698
2/4/14 8:00 AM	4.258345	4.767745	3.36999989	-1.39775	-0.88835
2/4/14 9:00 AM	4.259676	4.767741	3.31999993	-1.44774	-0.93968
2/4/14 10:00 AM	4.260976	4.767736	3.18000007	-1.58774	-1.08098
2/4/14 11:00 AM	4.262244	4.767732	2.98000002	-1.78773	-1.28224
2/4/14 12:00 PM	4.26348	4.767727	3	-1.76773	-1.26348
2/4/14 1:00 PM	4.264685	4.767724	3.19000006	-1.57772	-1.07468
2/4/14 2:00 PM	4.265858	4.76772	3.32999992	-1.43772	-0.93586
2/4/14 3:00 PM	4.267001	4.767716	3.23000002	-1.53772	-1.037
2/4/14 4:00 PM	4.268113	4.767713	3.21000004	-1.55771	-1.05811
2/4/14 5:00 PM	4.269194	4.767709	3.0999999	-1.66771	-1.16919
2/4/14 6:00 PM	4.270245	4.767706	2.98000002	-1.78771	-1.29024
2/4/14 7:00 PM	4.271265	4.767703	2.83999991	-1.9277	-1.43127
2/4/14 8:00 PM	4.272255	4.767699	8.65999985	3.892301	4.387745
2/4/14 9:00 PM	4.273216	4.767696	8.60999966	3.842304	4.336784
2/4/14 10:00 PM	4.274147	4.767694	4.26000023	-0.50769	-0.01415
2/4/14 11:00 PM	4.275049	4.767691	8.57999992	3.812309	4.304951
2/5/14 12:00 AM	4.275921	4.767689	8.55000019	3.782311	4.274079
2/5/14 1:00 AM	4.276765	4.767686	8.56000042	3.792314	4.283235

Simulation results, Observed data & Root Mean Square Error (R13 to R12.9)					
Date	**HEC-RAS (DO mg/L)**	**HCIS (DO mg/L)**	**Monitoring Station (DO mg/L)**	**HCIS Residual (DO)**	**HEC-RAS Residual (DO)**
2/5/14 2:00 AM	4.27758	4.767684	8.42000008	3.652316	4.14242
2/5/14 3:00 AM	4.278366	4.767681	3.82999992	-0.93768	-0.44837
2/5/14 4:00 AM	4.279124	4.767679	8.39999962	3.632321	4.120876
2/5/14 5:00 AM	4.279854	4.767677	8.36999989	3.602323	4.090146
2/5/14 6:00 AM	4.280556	4.767675	3.80999994	-0.95768	-0.47056
2/5/14 7:00 AM	4.281229	4.767673	8.13000011	3.362327	3.848771
2/5/14 8:00 AM	4.281876	4.767671	7.94999981	3.182329	3.668124
2/5/14 9:00 AM	4.282495	4.767669	7.98999977	3.222331	3.707505
2/5/14 10:00 AM	4.283087	4.767667	7.92000008	3.152333	3.636913
2/5/14 11:00 AM	4.283652	4.767666	7.8499999	3.082334	3.566348
2/5/14 12:00 PM	4.284191	4.767664	7.86999989	3.102336	3.585809
2/5/14 1:00 PM	4.284703	4.767663	7.8499999	3.082337	3.565297
2/5/14 2:00 PM	4.285189	4.767661	7.90999985	3.142339	3.624811
2/5/14 3:00 PM	4.285648	4.76766	7.96999979	3.20234	3.684352
2/5/14 4:00 PM	4.286082	4.767658	7.96000004	3.192342	3.673918
2/5/14 5:00 PM	4.286473	4.767657	3.16000009	-1.60766	-1.12647
2/5/14 6:00 PM	4.286818	4.767655	3.20000005	-1.56765	-1.08682
2/5/14 7:00 PM	4.287117	4.767654	3.18000007	-1.58765	-1.10712
2/5/14 8:00 PM	4.287371	4.767653	3.25999999	-1.50765	-1.02737
2/5/14 9:00 PM	4.287579	4.767652	3.3900001	-1.37765	-0.89758
2/5/14 10:00 PM	4.287751	4.767651	3.44000006	-1.32765	-0.84775
2/5/14 11:00 PM	4.287896	4.76765	3.45000005	-1.31765	-0.8379
2/6/14 12:00 AM	4.288013	4.767649	3.45000005	-1.31765	-0.83801
2/6/14 1:00 AM	4.288104	4.767648	3.45000005	-1.31765	-0.8381
2/6/14 2:00 AM	4.288167	4.767647	3.44000006	-1.32765	-0.84817
2/6/14 3:00 AM	4.288208	4.767646	3.5	-1.26765	-0.78821
2/6/14 4:00 AM	4.288228	4.767645	3.58999991	-1.17765	-0.69823
2/6/14 5:00 AM	4.288224	4.767644	3.68000007	-1.08764	-0.60822
2/6/14 6:00 AM	4.288199	4.767643	3.78999996	-0.97764	-0.4982
2/6/14 7:00 AM	4.288151	4.767643	3.8499999	-0.91764	-0.43815
2/6/14 8:00 AM	4.288082	4.767642	3.86999989	-0.89764	-0.41808
2/6/14 9:00 AM	4.287991	4.767641	3.8900001	-0.87764	-0.39799
2/6/14 10:00 AM	4.287879	4.767641	3.8900001	-0.87764	-0.39788
2/6/14 11:00 AM	4.287745	4.76764	3.88000011	-0.88764	-0.40774
2/6/14 12:00 PM	4.287589	4.76764	3.9000001	-0.86764	-0.38759
2/6/14 1:00 PM	4.287412	4.767639	3.93000007	-0.83764	-0.35741
2/6/14 2:00 PM	4.287214	4.767638	3.93000007	-0.83764	-0.35721
2/6/14 3:00 PM	4.286995	4.767638	3.95000005	-0.81764	-0.33699
2/6/14 4:00 PM	4.286756	4.767637	3.97000003	-0.79764	-0.31676
2/6/14 5:00 PM	4.286495	4.767636	4.46000004	-0.30764	0.173505
2/6/14 6:00 PM	4.286214	4.767636	4.26000023	-0.50764	-0.02621
2/6/14 7:00 PM	4.285912	4.767635	7.88999987	3.122365	3.604088
2/6/14 8:00 PM	4.284155	4.767635	7.75	2.982365	3.465845
2/6/14 9:00 PM	4.282419	4.767635	4.11999989	-0.64764	-0.16242
2/6/14 10:00 PM	4.280703	4.767634	4.30999994	-0.45763	0.029297
2/6/14 11:00 PM	4.279007	4.767634	7.46000004	2.692366	3.180993
2/7/14 12:00 AM	4.277331	4.767633	7.67000008	2.902367	3.392669
2/7/14 1:00 AM	4.275674	4.767633	5.03999996	0.272367	0.764326
2/7/14 2:00 AM	4.274035	4.767632	4.44000006	-0.32763	0.165965
2/7/14 3:00 AM	4.272412	4.767632	7.36999989	2.602368	3.097588
2/7/14 4:00 AM	4.270807	4.767632	7.63999987	2.872368	3.369193
2/7/14 5:00 AM	4.269218	4.767632	7.59000015	2.822368	3.320782
2/7/14 6:00 AM	4.267644	4.767632	7.51999998	2.752368	3.252356
2/7/14 7:00 AM	4.266087	4.767631	5.73000002	0.962369	1.463913
2/7/14 8:00 AM	4.264543	4.767631	5.84000015	1.072369	1.575457
2/7/14 9:00 AM	4.263013	4.767631	7.51999998	2.752369	3.256987
2/7/14 10:00 AM	4.261497	4.767631	7.82000017	3.052369	3.558503
2/7/14 11:00 AM	4.259994	4.76763	4.36999989	-0.39763	0.110006
2/7/14 12:00 PM	4.258504	4.76763	8.31999969	3.55237	4.061496
2/7/14 1:00 PM	4.257026	4.76763	4.07000017	-0.69763	-0.18703
2/7/14 2:00 PM	4.255559	4.76763	3.77999997	-0.98763	-0.47556
2/7/14 3:00 PM	4.254103	4.767629	8.73999977	3.972371	4.485897
2/7/14 4:00 PM	4.252658	4.767629	8.71000004	3.942371	4.457342
2/7/14 5:00 PM	4.251224	4.767629	8.69999981	3.932371	4.448776
2/7/14 6:00 PM	4.249799	4.767629	8.77000046	4.002371	4.520201
2/7/14 7:00 PM	4.248384	4.767628	3.82999992	-0.93763	-0.41838
2/7/14 8:00 PM	4.246978	4.767628	6.03000021	1.262372	1.783022
2/7/14 9:00 PM	4.24558	4.767628	4.36000013	-0.40763	0.11442
2/7/14 10:00 PM	4.244191	4.767628	8.77999973	4.012372	4.535809
2/7/14 11:00 PM	4.242809	4.767628	8.72999954	3.962372	4.487191
2/8/14 12:00 AM	4.241436	4.767628	8.76000023	3.992372	4.518564
2/8/14 1:00 AM	4.240069	4.767628	8.72000027	3.952372	4.479931
2/8/14 2:00 AM	4.238709	4.767628	4.86000013	0.092372	0.621291
2/8/14 3:00 AM	4.237356	4.767627	8.72000027	3.952373	4.482644
2/8/14 4:00 AM	4.236008	4.767627	8.69999981	3.932373	4.463992
2/8/14 5:00 AM	4.234667	4.767627	4.07999992	-0.68763	-0.15467
2/8/14 6:00 AM	4.233331	4.767627	5.69000006	0.922373	1.456669
2/8/14 7:00 AM	4.232	4.767627	8.68999958	3.922373	4.458
2/8/14 8:00 AM	4.230674	4.767627	8.64999962	3.882373	4.419326
2/8/14 9:00 AM	4.229352	4.767627	2.07999992	-2.68763	-2.14935
2/8/14 10:00 AM	4.228034	4.767626	2.11999989	-2.64763	-2.10803
2/8/14 11:00 AM	4.226721	4.767626	2.19000006	-2.57763	-2.03672
2/8/14 12:00 PM	4.225412	4.767626	2.26999998	-2.49763	-1.95541
2/8/14 1:00 PM	4.224105	4.767626	2.33999991	-2.42763	-1.88411
2/8/14 2:00 PM	4.222803	4.767626	2.4000001	-2.36763	-1.8228
2/8/14 3:00 PM	4.221502	4.767626	2.43000007	-2.33763	-1.7915
2/8/14 4:00 PM	4.220205	4.767626	2.47000003	-2.29763	-1.7502
2/8/14 5:00 PM	4.21891	4.767626	2.49000001	-2.27763	-1.72891
2/8/14 6:00 PM	4.217617	4.767626	2.45000005	-2.31763	-1.76762
2/8/14 7:00 PM	4.216326	4.767625	2.41000009	-2.35762	-1.80633

Simulation results, Observed data & Root Mean Square Error (R13 to R12.9)					
Date	**HEC-RAS (DO mg/L)**	**HCIS (DO mg/L)**	**Monitoring Station (DO mg/L)**	**HCIS Residual (DO)**	**HEC-RAS Residual (DO)**
2/8/14 8:00 PM	4.215037	4.767625	2.36999989	-2.39763	-1.84504
2/8/14 9:00 PM	4.21375	4.767625	2.3599999	-2.40763	-1.85375
2/8/14 10:00 PM	4.212464	4.767625	2.36999989	-2.39763	-1.84246
2/8/14 11:00 PM	4.211179	4.767625	2.42000008	-2.34762	-1.79118
2/9/14 12:00 AM	4.209895	4.767625	2.54999995	-2.21763	-1.6599
2/9/14 1:00 AM	4.208611	4.767625	2.6099999	-2.15763	-1.59861
2/9/14 2:00 AM	4.207329	4.767625	2.5999999	-2.16763	-1.60733
2/9/14 3:00 AM	4.206047	4.767625	2.73000002	-2.03762	-1.47605
2/9/14 4:00 AM	4.204764	4.767625	2.69000006	-2.07762	-1.51476
2/9/14 5:30 AM	4.203482	4.767625	2.55999994	-2.20763	-1.64348
2/9/14 6:30 AM	4.2022	4.767625	2.50999999	-2.25763	-1.6922
2/9/14 7:30 AM	4.200917	4.767625	2.42000008	-2.34762	-1.78092
2/9/14 8:30 AM	4.199634	4.767625	2.75999999	-2.00763	-1.43963
2/9/14 9:30 AM	4.19835	4.767625	2.46000004	-2.30762	-1.73835
2/9/14 10:30 AM	4.197065	4.767625	7.3499999	2.582375	3.152935
2/9/14 11:30 AM	4.195779	4.767625	7.88999987	3.122375	3.694221
2/9/14 12:30 PM	4.194492	4.767625	8.19999981	3.432375	4.005508
2/9/14 1:30 PM	4.193203	4.767625	8.40999985	3.642375	4.216797
2/9/14 2:30 PM	4.191914	4.767625	8.63000011	3.862375	4.438086
2/9/14 3:30 PM	4.190622	4.767625	8.71000004	3.942375	4.519378
2/9/14 4:30 PM	4.189328	4.767625	8.85999966	4.092375	4.670672
2/9/14 5:30 PM	4.188033	4.767625	8.93999958	4.172375	4.751967
2/9/14 6:30 PM	4.186736	4.767625	3.38000011	-1.38762	-0.80674
2/9/14 7:30 PM	4.185436	4.767625	3.43000007	-1.33762	-0.75544
2/9/14 8:30 PM	4.184134	4.767625	3.42000008	-1.34762	-0.76413
2/9/14 9:30 PM	4.182829	4.767625	2.02999997	-2.73763	-2.15283
2/9/14 10:30 PM	4.181523	4.767625	2.20000005	-2.56762	-1.98152
2/9/14 11:30 PM	4.180213	4.767625	2.3499999	-2.41763	-1.83021
2/10/14 12:30 AM	4.178901	4.767625	2.44000006	-2.32762	-1.7389
2/10/14 1:30 AM	4.177586	4.767625	2.48000002	-2.28762	-1.69759
2/10/14 2:30 AM	4.176268	4.767625	2.47000003	-2.29762	-1.70627
2/10/14 3:30 AM	4.174947	4.767625	2.51999998	-2.24763	-1.65495
2/10/14 4:30 AM	4.173623	4.767625	2.55999994	-2.20763	-1.61362
2/10/14 5:30 AM	4.172296	4.767625	2.5999999	-2.16763	-1.5723
2/10/14 6:30 AM	4.170965	4.767625	2.5999999	-2.16763	-1.57097
2/10/14 7:30 AM	4.169631	4.767625	2.6099999	-2.15763	-1.55963
2/10/14 8:30 AM	4.168293	4.767625	2.61999989	-2.14763	-1.54829
2/10/14 9:30 AM	4.166953	4.767625	2.6099999	-2.15763	-1.55695
2/10/14 10:30 AM	4.165609	4.767625	2.66000009	-2.10762	-1.50561
2/10/14 11:30 AM	4.164261	4.767625	2.67000008	-2.09762	-1.49426
2/10/14 12:30 PM	4.16291	4.767625	2.73000002	-2.03762	-1.43291
2/10/14 1:30 PM	4.161554	4.767625	2.79999995	-1.96763	-1.36155
2/10/14 2:30 PM	4.160195	4.767625	2.77999997	-1.98763	-1.3802
2/10/14 3:30 PM	4.158833	4.767625	2.63000011	-2.13762	-1.52883
2/10/14 4:30 PM	4.157466	4.767625	2.6500001	-2.11762	-1.50747
2/10/14 5:30 PM	4.156096	4.767625	2.55999994	-2.20763	-1.5961
2/10/14 6:30 PM	4.154722	4.767625	2.44000006	-2.32762	-1.71472
2/10/14 7:30 PM	4.153344	4.767625	2.21000004	-2.55762	-1.94334
2/10/14 8:30 PM	4.151962	4.767625	2.04999995	-2.71763	-2.10196
2/10/14 9:30 PM	4.150577	4.767625	2.00999999	-2.75763	-2.14058
2/10/14 10:30 PM	4.149187	4.767625	2.00999999	-2.75763	-2.13919
2/10/14 11:30 PM	4.147793	4.767625	1.97000003	-2.79762	-2.17779
2/11/14 12:30 AM	4.146395	4.767625	1.87	-2.89762	-2.27639
2/11/14 1:30 AM	4.144994	4.767625	1.95000005	-2.81762	-2.19499
2/11/14 2:30 AM	4.143588	4.767625	2.01999998	-2.74763	-2.12359
2/11/14 3:30 AM	4.142179	4.767625	2.06999993	-2.69763	-2.07218
2/11/14 4:30 AM	4.140765	4.767625	2.11999989	-2.64763	-2.02077
2/11/14 5:30 AM	4.139349	4.767625	2.19000006	-2.57762	-1.94935
2/11/14 6:30 AM	4.137928	4.767625	2.19000006	-2.57762	-1.94793
2/11/14 7:30 AM	4.136503	4.767625	2.19000006	-2.57762	-1.9465
2/11/14 8:30 AM	4.135075	4.767625	2.1500001	-2.61762	-1.98507
2/11/14 9:30 AM	4.133643	4.767625	2.1400001	-2.62762	-1.99364
2/11/14 10:30 AM	4.132207	4.767625	2.11999989	-2.64763	-2.01221
2/11/14 11:30 AM	4.130768	4.767625	2.08999991	-2.67763	-2.04077
2/11/14 12:30 PM	4.129326	4.767625	2.11999989	-2.64763	-2.00933
2/11/14 1:30 PM	4.12788	4.767625	2.16000009	-2.60762	-1.96788
2/11/14 2:30 PM	4.12643	4.767625	2.19000006	-2.57762	-1.93643
2/11/14 3:30 PM	4.124978	4.767625	2.20000005	-2.56762	-1.92498
2/11/14 4:30 PM	4.123521	4.767625	2.1500001	-2.61762	-1.97352
2/11/14 5:30 PM	4.122062	4.767625	2.11999989	-2.64763	-2.00206
2/11/14 6:30 PM	4.120599	4.767625	2.1099999	-2.65763	-2.0106
2/11/14 7:30 PM	4.119133	4.767625	2.0999999	-2.66763	-2.01913
2/11/14 8:30 PM	4.117664	4.767625	2.06999993	-2.69763	-2.04766
2/11/14 9:30 PM	4.116192	4.767625	2.74000001	-2.02762	-1.37619
2/11/14 10:30 PM	4.114717	4.767625	2.61999989	-2.14763	-1.49472
2/11/14 11:30 PM	4.113239	4.767625	2.6099999	-2.15763	-1.50324
2/12/14 12:30 AM	4.111758	4.767625	2.5999999	-2.16763	-1.51176
2/12/14 1:30 AM	4.110274	4.767625	2.57999992	-2.18763	-1.53027
2/12/14 2:30 AM	4.108788	4.767625	2.58999991	-2.17763	-1.51879
2/12/14 3:30 AM	4.107298	4.767625	2.5999999	-2.16763	-1.5073
2/12/14 4:30 AM	4.105805	4.767625	2.6099999	-2.15763	-1.49581
2/12/14 5:30 AM	4.10431	4.767625	2.6099999	-2.15763	-1.49431
2/12/14 6:30 AM	4.102811	4.767625	2.58999991	-2.17763	-1.51281
2/12/14 7:30 AM	4.101309	4.767625	2.55999994	-2.20763	-1.54131
2/12/14 8:30 AM	4.099805	4.767625	7.30999994	2.542375	3.210195
2/12/14 9:30 AM	4.098297	4.767625	2.5	-2.26763	-1.5983
2/12/14 10:30 AM	4.096786	4.767625	2.44000006	-2.32762	-1.65679
2/12/14 11:30 AM	4.095273	4.767625	2.3900001	-2.37762	-1.70527
2/12/14 12:30 PM	4.093757	4.767625	2.38000011	-2.38762	-1.71376
2/12/14 1:30 PM	4.092237	4.767625	2.42000008	-2.34762	-1.67224

Simulation results, Observed data & Root Mean Square Error (R13 to R12.9)					
Date	**HEC-RAS (DO mg/L)**	**HCIS (DO mg/L)**	**Monitoring Station (DO mg/L)**	**HCIS Residual (DO)**	**HEC-RAS Residual (DO)**
2/12/14 2:30 PM	4.090715	4.767625	2.43000007	-2.33762	-1.66071
2/12/14 3:30 PM	4.08919	4.767625	2.3499999	-2.41763	-1.73919
2/12/14 4:30 PM	4.087662	4.767625	2.22000003	-2.54762	-1.86766
2/12/14 5:30 PM	4.086131	4.767625	2.21000004	-2.55762	-1.87613
2/12/14 6:30 PM	4.084597	4.767625	2.13000011	-2.63762	-1.9546
2/12/14 7:30 PM	4.08306	4.767625	2.00999999	-2.75763	-2.07306
2/12/14 8:30 PM	4.08152	4.767625	1.96000004	-2.80762	-2.12152
2/12/14 9:30 PM	4.079977	4.767625	1.98000002	-2.78762	-2.09998
2/12/14 10:30 PM	4.078432	4.767625	1.95000005	-2.81762	-2.12843
2/12/14 11:30 PM	4.076883	4.767625	1.98000002	-2.78762	-2.09688
2/13/14 12:30 AM	4.075332	4.767625	2.02999997	-2.73763	-2.04533
2/13/14 1:30 AM	4.073778	4.767625	2.01999998	-2.74763	-2.05378
2/13/14 2:30 AM	4.072221	4.767625	2.02999997	-2.73763	-2.04222
2/13/14 3:30 AM	4.070662	4.767625	2.06999993	-2.69763	-2.00066
2/13/14 4:30 AM	4.069099	4.767625	2.08999991	-2.67763	-1.9791
2/13/14 5:30 AM	4.067535	4.767625	2.11999989	-2.64763	-1.94754
2/13/14 6:30 AM	4.065968	4.767625	2.0999999	-2.66763	-1.96597
2/13/14 7:30 AM	4.064398	4.767625	2.05999994	-2.70763	-2.0044
2/13/14 8:30 AM	4.062826	4.767625	1.99000001	-2.77762	-2.07283
2/13/14 9:30 AM	4.061252	4.767625	1.96000004	-2.80762	-2.10125
2/13/14 10:30 AM	4.059675	4.767625	1.99000001	-2.77762	-2.06967
2/13/14 11:30 AM	4.058096	4.767625	2.04999995	-2.71763	-2.0081
2/13/14 12:30 PM	4.056516	4.767625	2.04999995	-2.71763	-2.00652
2/13/14 1:30 PM	4.054933	4.767625	2.02999997	-2.73763	-2.02493
2/13/14 2:30 PM	4.053348	4.767625	1.98000002	-2.78762	-2.07335
2/13/14 3:30 PM	4.051761	4.767625	1.90999997	-2.85763	-2.14176
2/13/14 4:30 PM	4.050171	4.767625	1.88	-2.88763	-2.17017
2/13/14 5:30 PM	4.048581	4.767625	1.87	-2.89762	-2.17858
2/13/14 6:30 PM	4.046988	4.767625	1.83000004	-2.93762	-2.21699
2/13/14 7:30 PM	4.045394	4.767625	1.85000002	-2.91762	-2.19539
2/13/14 8:30 PM	4.043798	4.767625	1.90999997	-2.85763	-2.1338
2/13/14 9:30 PM	4.0422	4.767625	4.53000021	-0.23762	0.4878
2/13/14 10:30 PM	4.040601	4.767625	4.55000019	-0.21762	0.509399
2/13/14 11:30 PM	4.039001	4.767625	4.53999996	-0.22763	0.500999
2/14/14 12:30 AM	4.037398	4.767625	4.51999998	-0.24763	0.482602
2/14/14 1:30 AM	4.035795	4.767625	4.53000021	-0.23762	0.494205
2/14/14 2:30 AM	4.03419	4.767625	4.48999977	-0.27763	0.45581
2/14/14 3:30 AM	4.032585	4.767625	4.48000002	-0.28762	0.447415
2/14/14 4:30 AM	4.030977	4.767625	4.46000004	-0.30762	0.429023
2/14/14 5:30 AM	4.029369	4.767625	4.38999987	-0.37763	0.360631
2/14/14 6:30 AM	4.02776	4.767625	4.32000017	-0.44762	0.29224
2/14/14 7:30 AM	4.02615	4.767625	4.21999979	-0.54763	0.19385
2/14/14 8:30 AM	4.024539	4.767625	4.0999999	-0.66763	0.075461
2/14/14 9:30 AM	4.022928	4.767625	4.07000017	-0.69762	0.047072
2/14/14 10:30 AM	4.021316	4.767625	4.11000013	-0.65762	0.088684
2/14/14 11:30 AM	4.019702	4.767625	4.03999996	-0.72763	0.020298
2/14/14 12:30 PM	4.018089	4.767625	3.95000005	-0.81762	-0.06809
2/14/14 1:30 PM	4.016475	4.767625	3.88000011	-0.88762	-0.13647
2/14/14 2:30 PM	4.01486	4.767625	3.88000011	-0.88762	-0.13486
2/14/14 3:30 PM	4.013246	4.767625	3.98000002	-0.78762	-0.03325
2/14/14 4:30 PM	4.011631	4.767625	4.07999992	-0.68763	0.068369
2/14/14 5:30 PM	4.010015	4.767625	4.15999985	-0.60763	0.149985
2/14/14 6:30 PM	4.008399	4.767625	4.21999979	-0.54763	0.211601
2/14/14 7:30 PM	4.006784	4.767625	4.19999981	-0.56763	0.193216
2/14/14 8:30 PM	4.005168	4.767625	4.23000002	-0.53762	0.224832
2/14/14 9:30 PM	4.003553	4.767625	4.19000006	-0.57762	0.186447
2/14/14 10:30 PM	4.001938	4.767625	4.07999992	-0.68763	0.078062
2/14/14 11:30 PM	4.000323	4.767625	4.01999998	-0.74763	0.019677
2/15/14 12:30 AM	3.998708	4.767625	3.97000003	-0.79762	-0.02871
2/15/14 1:30 AM	3.997093	4.767625	3.8599999	-0.90763	-0.13709
2/15/14 2:30 AM	3.995479	4.767625	3.78999996	-0.97763	-0.20548
2/15/14 3:30 AM	3.993866	4.767625	3.71000004	-1.05762	-0.28387
2/15/14 4:30 AM	3.992253	4.767625	3.57999992	-1.18763	-0.41225
2/15/14 5:30 AM	3.99064	4.767625	3.45000005	-1.31762	-0.54064
2/15/14 6:30 AM	3.989028	4.767625	3.3499999	-1.41763	-0.63903
2/15/14 7:30 AM	3.987417	4.767625	3.33999991	-1.42763	-0.64742
2/15/14 8:30 AM	3.985806	4.767625	3.44000006	-1.32762	-0.54581
2/15/14 9:30 AM	3.984197	4.767625	3.44000006	-1.32762	-0.5442
2/15/14 10:30 AM	3.982588	4.767625	3.1400001	-1.62762	-0.84259
2/15/14 11:30 AM	3.98098	4.767625	2.5	-2.26763	-1.48098
2/15/14 12:30 PM	3.979373	4.767625	1.52999997	-3.23763	-2.44937
2/15/14 1:30 PM	3.977767	4.767625	0.62	-4.14762	-3.35777
2/15/14 2:30 PM	3.976162	4.767625	1.63999999	-3.12763	-2.33616
2/15/14 3:30 PM	3.974558	4.767625	2.38000011	-2.38762	-1.59456
2/15/14 4:30 PM	3.972955	4.767625	2.55999994	-2.20763	-1.41296
2/15/14 5:30 PM	3.971354	4.767625	1.79999995	-2.96763	-2.17135
2/15/14 6:30 PM	3.969754	4.767625	3.45000005	-1.31762	-0.51975
2/15/14 7:30 PM	3.968155	4.767625	3.51999998	-1.24763	-0.44816
2/15/14 8:30 PM	3.966558	4.767625	3.05999994	-1.70763	-0.90656
2/15/14 9:30 PM	3.964961	4.767625	4.03999996	-0.72763	0.075039
2/15/14 10:30 PM	3.963367	4.767625	4.01000023	-0.75762	0.046633
2/15/14 11:30 PM	3.961774	4.767625	4	-0.76763	0.038226
2/16/14 12:30 AM	3.960183	4.767625	4	-0.76763	0.039817
2/16/14 1:30 AM	3.958593	4.767625	4	-0.76763	0.041407
2/16/14 2:30 AM	3.957005	4.767625	4.01000023	-0.75762	0.052995
2/16/14 3:30 AM	3.955418	4.767625	4.05999994	-0.70763	0.104582
2/16/14 4:30 AM	3.953834	4.767625	4.05000019	-0.71762	0.096166
2/16/14 5:30 AM	3.95225	4.767625	4.05000019	-0.71762	0.09775
2/16/14 6:30 AM	3.950669	4.767625	4.01000023	-0.75762	0.059331
2/16/14 7:30 AM	3.949089	4.767625	3.9000001	-0.86762	-0.04909

Simulation results, Observed data & Root Mean Square Error (R13 to R12.9)					
Date	**HEC-RAS (DO mg/L)**	**HCIS (DO mg/L)**	**Monitoring Station (DO mg/L)**	**HCIS Residual (DO)**	**HEC-RAS Residual (DO)**
2/16/14 8:30 AM	3.947511	4.767625	3.80999994	-0.95763	-0.13751
2/16/14 9:30 AM	3.945935	4.767625	3.76999998	-0.99763	-0.17594
2/16/14 10:30 AM	3.94436	4.767625	3.8499999	-0.91763	-0.09436
2/16/14 11:30 AM	3.943071	4.767625	4.07000017	-0.69762	0.126929
2/16/14 12:30 PM	3.941775	4.767625	4.21000004	-0.55762	0.268225
2/16/14 1:30 PM	3.940472	4.767625	4.28999996	-0.47763	0.349528
2/16/14 2:30 PM	3.939162	4.767625	4.23999977	-0.52763	0.300838
2/16/14 3:30 PM	3.937846	4.767625	4.19999981	-0.56763	0.262154
2/16/14 4:30 PM	3.936524	4.767625	4.0999999	-0.66763	0.163476
2/16/14 5:30 PM	3.935196	4.767625	4.05000019	-0.71762	0.114804
2/16/14 6:30 PM	3.933861	4.767625	4.0999999	-0.66763	0.166139
2/16/14 7:30 PM	3.932521	4.767625	4.17999983	-0.58763	0.247479
2/16/14 8:30 PM	3.931175	4.767625	4.21999979	-0.54763	0.288825
2/16/14 9:30 PM	3.929822	4.767625	4.23999977	-0.52763	0.310178
2/16/14 10:30 PM	3.928464	4.767625	4.23000002	-0.53762	0.301536
2/16/14 11:30 PM	3.927101	4.767625	4.36999989	-0.39763	0.442899
2/17/14 12:30 AM	3.925732	4.767625	4.44000006	-0.32762	0.514268
2/17/14 1:30 AM	3.924357	4.767625	4.51000023	-0.25762	0.585643
2/17/14 2:30 AM	3.922977	4.767625	4.53999996	-0.22763	0.617023
2/17/14 3:30 AM	3.921592	4.767625	4.51000023	-0.25762	0.588408
2/17/14 4:30 AM	3.920202	4.767625	4.51999998	-0.24763	0.599798
2/17/14 5:30 AM	3.918807	4.767625	4.53999996	-0.22763	0.621193
2/17/14 6:30 AM	3.917407	4.767625	4.53000021	-0.23762	0.612593
2/17/14 7:30 AM	3.916002	4.767625	4.48000002	-0.28762	0.563998
2/17/14 8:30 AM	3.914593	4.767625	4.44000006	-0.32762	0.525407
2/17/14 9:30 AM	3.913179	4.767625	4.44000006	-0.32762	0.526821
2/17/14 10:30 AM	3.911761	4.767625	4.44000006	-0.32762	0.528239
2/17/14 11:30 AM	3.910339	4.767625	4.44000006	-0.32762	0.529661
2/17/14 12:30 PM	3.908913	4.767625	4.42999983	-0.33763	0.521087
2/17/14 1:30 PM	3.907482	4.767625	4.38999987	-0.37763	0.482518
2/17/14 2:30 PM	3.906048	4.767625	4.38999987	-0.37763	0.483952
2/17/14 3:30 PM	3.90461	4.767625	4.36999989	-0.39763	0.46539
2/17/14 4:30 PM	3.903169	4.767625	4.3499999	-0.41763	0.446831
2/17/14 5:30 PM	3.901724	4.767625	4.3499999	-0.41763	0.448276
2/17/14 6:30 PM	3.900275	4.767625	4.36000013	-0.40762	0.459725
2/17/14 7:30 PM	3.898823	4.767625	4.42000008	-0.34762	0.521177
2/17/14 8:30 PM	3.897368	4.767625	4.48000002	-0.28762	0.582632
2/17/14 9:30 PM	3.89591	4.767625	3.45000005	-1.31762	-0.44591
2/17/14 10:30 PM	3.894449	4.767625	3.48000002	-1.28762	-0.41445
2/17/14 11:30 PM	3.892985	4.767625	3.53999996	-1.22763	-0.35299
2/18/14 12:30 AM	3.891518	4.767625	3.63000011	-1.13762	-0.26152
2/18/14 1:30 AM	3.890048	4.767625	3.75	-1.01763	-0.14005
2/18/14 2:30 AM	3.888576	4.767625	3.8499999	-0.91763	-0.03858
2/18/14 3:30 AM	3.887101	4.767625	4.01000023	-0.75762	0.122899
2/18/14 4:30 AM	3.885623	4.767625	4.19000006	-0.57762	0.304377
2/18/14 5:30 AM	3.884143	4.767625	4.38000011	-0.38762	0.495857
2/18/14 6:30 AM	3.88266	4.767625	4.48999977	-0.27763	0.60734
2/18/14 7:30 AM	3.881175	4.767625	4.55000019	-0.21762	0.668825
2/18/14 8:30 AM	3.879688	4.767625	4.57000017	-0.19762	0.690312
2/18/14 9:30 AM	3.878197	4.767625	4.51999998	-0.24763	0.641803
2/18/14 10:30 AM	3.876705	4.767625	4.42000008	-0.34762	0.543295
2/18/14 11:30 AM	3.87521	4.767625	4.21000004	-0.55762	0.33479
2/18/14 12:30 PM	3.873713	4.767625	4.1500001	-0.61762	0.276287
2/18/14 1:30 PM	3.872214	4.767625	4.13999987	-0.62763	0.267786
2/18/14 2:30 PM	3.870712	4.767625	3.8499999	-0.91763	-0.02071
2/18/14 3:30 PM	3.869208	4.767625	3.66000009	-1.10762	-0.20921
2/18/14 4:30 PM	3.867702	4.767625	3.63000011	-1.13762	-0.2377
2/18/14 5:30 PM	3.866194	4.767625	3.5999999	-1.16763	-0.26619
2/18/14 6:30 PM	3.864684	4.767625	3.52999997	-1.23763	-0.33468
2/18/14 7:30 PM	3.863172	4.767625	3.5	-1.26763	-0.36317
2/18/14 8:30 PM	3.861658	4.767625	3.5	-1.26763	-0.36166
2/18/14 9:30 PM	3.860142	4.767625	3.3900001	-1.37762	-0.47014
2/18/14 10:30 PM	3.858624	4.767625	3.3499999	-1.41763	-0.50862
2/18/14 11:30 PM	3.857103	4.767625	3.33999991	-1.42763	-0.5171
2/19/14 12:30 AM	3.855582	4.767625	3.43000007	-1.33762	-0.42558
2/19/14 1:30 AM	3.854058	4.767625	3.36999989	-1.39763	-0.48406
2/19/14 2:30 AM	3.852533	4.767625	3.38000011	-1.38762	-0.47253
2/19/14 3:30 AM	3.851006	4.767625	3.44000006	-1.32762	-0.41101
2/19/14 4:30 AM	3.849477	4.767625	3.55999994	-1.20763	-0.28948
2/19/14 5:30 AM	3.847947	4.767625	3.86999989	-0.89763	0.022053
2/19/14 6:30 AM	3.846416	4.767625	4.23000002	-0.53762	0.383584
2/19/14 7:30 AM	3.844883	4.767625	4.32000017	-0.44762	0.475117
2/19/14 8:30 AM	3.843349	4.767625	4.28999996	-0.47763	0.446651
2/19/14 9:30 AM	3.841813	4.767625	4.28999996	-0.47763	0.448187
2/19/14 10:30 AM	3.840277	4.767625	4.26999998	-0.49763	0.429723
2/19/14 11:30 AM	3.838739	4.767625	4.25	-0.51763	0.411261
2/19/14 12:30 PM	3.8372	4.767625	4.21999979	-0.54763	0.3828
2/19/14 1:30 PM	3.83566	4.767625	4.17999983	-0.58763	0.34434
2/19/14 2:30 PM	3.83412	4.767625	4.17999983	-0.58763	0.34588
2/19/14 3:30 PM	3.832578	4.767625	4.15999985	-0.60763	0.327422
2/19/14 4:30 PM	3.831036	4.767625	4.17000008	-0.59762	0.338964
2/19/14 5:30 PM	3.829493	4.767625	4.13000011	-0.63762	0.300507
2/19/14 6:30 PM	3.827949	4.767625	4.07999992	-0.68763	0.252051
2/19/14 7:30 PM	3.826405	4.767625	4.07000017	-0.69762	0.243595
2/19/14 8:30 PM	3.82486	4.767625	4.05000019	-0.71762	0.22514
2/19/14 9:30 PM	3.823314	4.767625	4	-0.76763	0.176686
2/19/14 10:30 PM	3.821769	4.767625	4	-0.76763	0.178231
2/19/14 11:30 PM	3.820222	4.767625	4.05999994	-0.70763	0.239778
2/20/14 12:30 AM	3.818676	4.767625	4.13999987	-0.62763	0.321324
2/20/14 1:30 AM	3.817129	4.767625	4.26999998	-0.49763	0.452871

Simulation results, Observed data & Root Mean Square Error (R13 to R12.9)					
Date	**HEC-RAS (DO mg/L)**	**HCIS (DO mg/L)**	**Monitoring Station (DO mg/L)**	**HCIS Residual (DO)**	**HEC-RAS Residual (DO)**
2/20/14 2:30 AM	3.815582	4.767625	4.36999989	-0.39763	0.554418
2/20/14 3:30 AM	3.814036	4.767625	4.44999981	-0.31763	0.635964
2/20/14 4:30 AM	3.812489	4.767625	4.53999996	-0.22763	0.727511
2/20/14 5:30 AM	3.810943	4.767625	4.57000017	-0.19762	0.759057
2/20/14 6:30 AM	3.809398	4.767625	4.55000019	-0.21762	0.740602
2/20/14 7:30 AM	3.807853	4.767625	4.46000004	-0.30762	0.652147
2/20/14 8:30 AM	3.806309	4.767625	4.42000008	-0.34762	0.613691
2/20/14 9:30 AM	3.804765	4.767625	4.3499999	-0.41763	0.545235
2/20/14 10:30 AM	3.803223	4.767625	4.30000019	-0.46762	0.496777
2/20/14 11:30 AM	3.801682	4.767625	4.23000002	-0.53762	0.428318
2/20/14 12:30 PM	3.800141	4.767625	4.15999985	-0.60763	0.359859
2/20/14 1:30 PM	3.798601	4.767625	3.98000002	-0.78762	0.181399
2/20/14 2:30 PM	3.797063	4.767625	4.03000021	-0.73762	0.232937
2/20/14 3:30 PM	3.795525	4.767625	4.03999996	-0.72763	0.244475
2/20/14 4:30 PM	3.793989	4.767625	3.98000002	-0.78762	0.186011
2/20/14 5:30 PM	3.792454	4.767625	3.8900001	-0.87762	0.097546
2/20/14 6:30 PM	3.79092	4.767625	3.8499999	-0.91763	0.05908
2/20/14 7:30 PM	3.789388	4.767625	3.8499999	-0.91763	0.060612
2/20/14 8:30 PM	3.787857	4.767625	3.82999992	-0.93763	0.042143
2/20/14 9:30 PM	3.786327	4.767625	3.8499999	-0.91763	0.063673
2/20/14 10:30 PM	3.784799	4.767625	3.79999995	-0.96763	0.015201
2/20/14 11:30 PM	3.783273	4.767625	3.69000006	-1.07762	-0.09327
2/21/14 12:30 AM	3.781748	4.767625	3.61999989	-1.14763	-0.16175
2/21/14 1:30 AM	3.780224	4.767625	3.58999991	-1.17763	-0.19022
2/21/14 2:30 AM	3.778702	4.767625	3.63000011	-1.13762	-0.1487
2/21/14 3:30 AM	3.777181	4.767625	3.72000003	-1.04762	-0.05718
2/21/14 4:30 AM	3.775662	4.767625	3.78999996	-0.97763	0.014338
2/21/14 5:30 AM	3.774144	4.767625	3.98000002	-0.78762	0.205856
2/21/14 6:30 AM	3.772628	4.767625	4.28999996	-0.47763	0.517372
2/21/14 7:30 AM	3.771113	4.767625	4.34000015	-0.42762	0.568887
2/21/14 8:30 AM	3.769599	4.767625	4.34000015	-0.42762	0.570401
2/21/14 9:30 AM	3.768086	4.767625	4.28000021	-0.48762	0.511914
2/21/14 10:30 AM	3.766574	4.767625	4.21999979	-0.54763	0.453426
2/21/14 11:30 AM	3.765064	4.767625	4.13000011	-0.63762	0.364936
2/21/14 12:30 PM	3.763555	4.767625	4.09000015	-0.67762	0.326445
2/21/14 1:30 PM	3.762046	4.767625	4.03000021	-0.73762	0.267954
2/21/14 2:30 PM	3.760539	4.767625	3.97000003	-0.79762	0.209461
2/21/14 3:30 PM	3.759033	4.767625	3.9000001	-0.86762	0.140967
2/21/14 4:30 PM	3.757528	4.767625	3.80999994	-0.95763	0.052472
2/21/14 5:30 PM	3.756023	4.767625	3.73000002	-1.03762	-0.02602
2/21/14 6:30 PM	3.75452	4.767625	3.6500001	-1.11762	-0.10452
2/21/14 7:30 PM	3.753017	4.767625	3.55999994	-1.20763	-0.19302
2/21/14 8:30 PM	3.751516	4.767625	3.47000003	-1.29762	-0.28152
2/21/14 9:30 PM	3.750015	4.767625	3.5	-1.26763	-0.25002
2/21/14 10:30 PM	3.748514	4.767625	3.25999999	-1.50763	-0.48851
2/21/14 11:30 PM	3.747015	4.767625	3.28999996	-1.47763	-0.45702
2/22/14 12:30 AM	3.745516	4.767625	3.29999995	-1.46763	-0.44552
2/22/14 1:30 AM	3.744018	4.767625	3.3499999	-1.41763	-0.39402
2/22/14 2:30 AM	3.74252	4.767625	3.4000001	-1.36762	-0.34252
2/22/14 3:30 AM	3.741022	4.767625	3.5	-1.26763	-0.24102
2/22/14 4:30 AM	3.739525	4.767625	3.58999991	-1.17763	-0.14953
2/22/14 5:30 AM	3.738027	4.767625	3.6099999	-1.15763	-0.12803
2/22/14 6:30 AM	3.73653	4.767625	3.6400001	-1.12762	-0.09653
2/22/14 7:30 AM	3.735032	4.767625	3.67000008	-1.09762	-0.06503
2/22/14 8:30 AM	3.733535	4.767625	3.66000009	-1.10762	-0.07353
2/22/14 9:30 AM	3.732036	4.767625	3.6500001	-1.11762	-0.08204
2/22/14 10:30 AM	3.730537	4.767625	3.61999989	-1.14763	-0.11054
2/22/14 11:30 AM	3.729038	4.767625	3.55999994	-1.20763	-0.16904
2/22/14 12:30 PM	3.727538	4.767625	3.52999997	-1.23763	-0.19754
2/22/14 1:30 PM	3.726037	4.767625	3.47000003	-1.29762	-0.25604
2/22/14 2:30 PM	3.724535	4.767625	3.52999997	-1.23763	-0.19454
2/22/14 3:30 PM	3.723031	4.767625	3.6500001	-1.11762	-0.07303
2/22/14 4:30 PM	3.721526	4.767625	3.6500001	-1.11762	-0.07153
2/22/14 5:30 PM	3.72002	4.767625	3.6500001	-1.11762	-0.07002
2/22/14 6:30 PM	3.718513	4.767625	3.63000011	-1.13762	-0.08851
2/22/14 7:30 PM	3.717003	4.767625	3.56999993	-1.19763	-0.147
2/22/14 8:30 PM	3.715492	4.767625	3.55999994	-1.20763	-0.15549
2/22/14 9:30 PM	3.713979	4.767625	3.5	-1.26763	-0.21398
2/22/14 10:30 PM	3.712464	4.767625	3.46000004	-1.30762	-0.25246
2/22/14 11:30 PM	3.710946	4.767625	3.41000009	-1.35762	-0.30095
2/23/14 12:30 AM	3.709426	4.767625	3.23000002	-1.53762	-0.47943
2/23/14 1:30 AM	3.707904	4.767625	3.29999995	-1.46763	-0.4079
2/23/14 2:30 AM	3.706379	4.767625	4.11999989	-0.64763	0.413621
2/23/14 3:30 AM	3.704852	4.767625	4.07000017	-0.69762	0.365148
2/23/14 4:30 AM	3.703322	4.767625	4	-0.76763	0.296678
2/23/14 5:30 AM	3.701788	4.767625	3.98000002	-0.78762	0.278212
2/23/14 6:30 AM	3.700252	4.767625	3.91000009	-0.85762	0.209748
2/23/14 7:30 AM	3.698712	4.767625	3.91000009	-0.85762	0.211288
2/23/14 8:30 AM	3.697169	4.767625	3.94000006	-0.82762	0.242831
2/23/14 9:30 AM	3.695623	4.767625	3.96000004	-0.80762	0.264377
2/23/14 10:30 AM	3.694073	4.767625	3.96000004	-0.80762	0.265927
2/23/14 11:30 AM	3.692519	4.767625	4.01999998	-0.74763	0.327481
2/23/14 12:30 PM	3.690961	4.767625	4.09000015	-0.67762	0.399039
2/23/14 1:30 PM	3.689399	4.767625	4.13000011	-0.63762	0.440601
2/23/14 2:30 PM	3.687833	4.767625	4.15999985	-0.60763	0.472167
2/23/14 3:30 PM	3.686263	4.767625	4.19000006	-0.57762	0.503737
2/23/14 4:30 PM	3.684689	4.767625	4.11999989	-0.64763	0.435311
2/23/14 5:30 PM	3.68311	4.767625	3.79999995	-0.96763	0.11689
2/23/14 6:30 PM	3.681527	4.767625	4.21000004	-0.55762	0.528473
2/23/14 7:30 PM	3.67994	4.767625	3.44000006	-1.32762	-0.23994

Simulation results, Observed data & Root Mean Square Error (R13 to R12.9)					
Date	**HEC-RAS (DO mg/L)**	**HCIS (DO mg/L)**	**Monitoring Station (DO mg/L)**	**HCIS Residual (DO)**	**HEC-RAS Residual (DO)**
2/23/14 8:30 PM	3.678348	4.767625	3.3900001	-1.37762	-0.28835
2/23/14 9:30 PM	3.676751	4.767625	3.33999991	-1.42763	-0.33675
2/23/14 10:30 PM	3.675151	4.767625	2.26999998	-2.49763	-1.40515
2/23/14 11:30 PM	3.673545	4.767625	2.51999998	-2.24763	-1.15355
2/24/14 12:30 AM	3.671935	4.767625	2.73000002	-2.03762	-0.94193
2/24/14 1:30 AM	3.670321	4.767625	2.86999989	-1.89763	-0.80032
2/24/14 2:30 AM	3.668701	4.767625	2.95000005	-1.81762	-0.7187
2/24/14 3:30 AM	3.667078	4.767625	2.99000001	-1.77762	-0.67708
2/24/14 4:30 AM	3.665449	4.767625	3.05999994	-1.70763	-0.60545
2/24/14 5:30 AM	3.663817	4.767625	3.0999999	-1.66763	-0.56382
2/24/14 6:30 AM	3.662179	4.767625	3.13000011	-1.63762	-0.53218
2/24/14 7:30 AM	3.660537	4.767625	3.11999989	-1.64763	-0.54054
2/24/14 8:30 AM	3.658891	4.767625	3.11999989	-1.64763	-0.53889
2/24/14 9:30 AM	3.65724	4.767625	3.08999991	-1.67763	-0.56724
2/24/14 10:30 AM	3.655584	4.767625	3.05999994	-1.70763	-0.59558
2/24/14 11:30 AM	3.653924	4.767625	3.06999993	-1.69763	-0.58392
2/24/14 12:30 PM	3.65226	4.767625	3.16000009	-1.60762	-0.49226
2/24/14 1:30 PM	3.65059	4.767625	3.21000004	-1.55762	-0.44059
2/24/14 2:30 PM	3.648916	4.767625	3.3599999	-1.40763	-0.28892
2/24/14 3:30 PM	3.647238	4.767625	3.45000005	-1.31762	-0.19724
2/24/14 4:30 PM	3.645555	4.767625	3.5	-1.26763	-0.14556
2/24/14 5:30 PM	3.643867	4.767625	3.47000003	-1.29762	-0.17387
2/24/14 6:30 PM	3.642175	4.767625	3.38000011	-1.38762	-0.26217
2/24/14 7:30 PM	3.640479	4.767625	3.24000001	-1.52762	-0.40048
2/24/14 8:30 PM	3.638778	4.767625	3.16000009	-1.60762	-0.47878
2/24/14 9:30 PM	3.637074	4.767625	3.01999998	-1.74763	-0.61707
2/24/14 10:30 PM	3.635365	4.767625	2.81999993	-1.94763	-0.81537
2/24/14 11:30 PM	3.633652	4.767625	2.68000007	-2.08762	-0.95365
2/25/14 12:30 AM	3.631936	4.767625	2.56999993	-2.19763	-1.06194
2/25/14 1:30 AM	3.630216	4.767625	2.57999992	-2.18763	-1.05022
2/25/14 2:30 AM	3.628493	4.767625	2.52999997	-2.23763	-1.09849
2/25/14 3:30 AM	3.626766	4.767625	2.61999989	-2.14763	-1.00677
2/25/14 4:30 AM	3.625036	4.767625	2.6500001	-2.11762	-0.97504
2/25/14 5:30 AM	3.623304	4.767625	2.75	-2.01763	-0.8733
2/25/14 6:30 AM	3.621568	4.767625	2.95000005	-1.81762	-0.67157
2/25/14 7:30 AM	3.619831	4.767625	3.16000009	-1.60762	-0.45983
2/25/14 8:30 AM	3.618091	4.767625	3.21000004	-1.55762	-0.40809
2/25/14 9:30 AM	3.616348	4.767625	3.17000008	-1.59762	-0.44635
2/25/14 10:30 AM	3.614604	4.767625	3.1500001	-1.61762	-0.4646
2/25/14 11:30 AM	3.612857	4.767625	3.0999999	-1.66763	-0.51286
2/25/14 12:30 PM	3.611109	4.767625	3.03999996	-1.72763	-0.57111
2/25/14 1:30 PM	3.60936	4.767625	3.05999994	-1.70763	-0.54936
2/25/14 2:30 PM	3.607608	4.767625	3.07999992	-1.68763	-0.52761
2/25/14 3:30 PM	3.605856	4.767625	3.07999992	-1.68763	-0.52586
2/25/14 4:30 PM	3.604102	4.767625	3.08999991	-1.67763	-0.5141
2/25/14 5:30 PM	3.602347	4.767625	3.0999999	-1.66763	-0.50235
2/25/14 6:30 PM	3.600591	4.767625	3.1400001	-1.62762	-0.46059
2/25/14 7:30 PM	3.598835	4.767625	3.16000009	-1.60762	-0.43883
2/25/14 8:30 PM	3.597078	4.767625	3.20000005	-1.56762	-0.39708
2/25/14 9:30 PM	3.59532	4.767625	3.23000002	-1.53762	-0.36532
2/25/14 10:30 PM	3.593562	4.767625	1.11000001	-3.65762	-2.48356
2/25/14 11:30 PM	3.591804	4.767625	1.30999994	-3.45763	-2.2818
2/26/14 12:30 AM	3.590046	4.767625	1.75999999	-3.00763	-1.83005
2/26/14 1:30 AM	3.588287	4.767625	2.24000001	-2.52762	-1.34829
2/26/14 2:30 AM	3.586529	4.767625	2.61999989	-2.14763	-0.96653
2/26/14 3:30 AM	3.58477	4.767625	2.81999993	-1.94763	-0.76477
2/26/14 4:30 AM	3.583012	4.767625	2.94000006	-1.82762	-0.64301
2/26/14 5:30 AM	3.581253	4.767625	2.99000001	-1.77762	-0.59125
2/26/14 6:30 AM	3.579495	4.767625	3.04999995	-1.71763	-0.5295
2/26/14 7:30 AM	3.577738	4.767625	3.0999999	-1.66763	-0.47774
2/26/14 8:30 AM	3.57598	4.767625	3.19000006	-1.57762	-0.38598
2/26/14 9:30 AM	3.574223	4.767625	3.25999999	-1.50763	-0.31422
2/26/14 10:30 AM	3.572466	4.767625	3.29999995	-1.46763	-0.27247
2/26/14 11:30 AM	3.57071	4.767625	3.33999991	-1.42763	-0.23071
2/26/14 12:30 PM	3.568954	4.767625	3.3499999	-1.41763	-0.21895
2/26/14 1:30 PM	3.567199	4.767625	3.3499999	-1.41763	-0.2172
2/26/14 2:30 PM	3.565445	4.767625	3.44000006	-1.32762	-0.12544
2/26/14 3:30 PM	3.563692	4.767625	3.49000001	-1.27762	-0.07369
2/26/14 4:30 PM	3.561939	4.767625	3.46000004	-1.30762	-0.10194
2/26/14 5:30 PM	3.560188	4.767625	3.44000006	-1.32762	-0.12019
2/26/14 6:30 PM	3.558439	4.767625	3.27999997	-1.48763	-0.27844
2/26/14 7:30 PM	3.55669	4.767625	3.13000011	-1.63762	-0.42669
2/26/14 8:30 PM	3.554944	4.767625	2.94000006	-1.82762	-0.61494
2/26/14 9:30 PM	3.553199	4.767625	2.72000003	-2.04762	-0.8332
2/26/14 10:30 PM	3.551456	4.767625	2.6099999	-2.15763	-0.94146
2/26/14 11:30 PM	3.549716	4.767625	2.6099999	-2.15763	-0.93972
2/27/14 12:30 AM	3.547977	4.767625	2.66000009	-2.10762	-0.88798
2/27/14 1:30 AM	3.546241	4.767625	2.66000009	-2.10762	-0.88624
2/27/14 2:30 AM	3.544507	4.767625	2.58999991	-2.17763	-0.95451
2/27/14 3:30 AM	3.542775	4.767625	2.57999992	-2.18763	-0.96278
2/27/14 4:30 AM	3.541046	4.767625	2.57999992	-2.18763	-0.96105
2/27/14 5:30 AM	3.53932	4.767625	2.58999991	-2.17763	-0.94932
2/27/14 6:30 AM	3.537596	4.767625	2.58999991	-2.17763	-0.9476
2/27/14 7:30 AM	3.535875	4.767625	2.58999991	-2.17763	-0.94588
2/27/14 8:30 AM	3.534157	4.767625	2.58999991	-2.17763	-0.94416
2/27/14 9:30 AM	3.532442	4.767625	2.54999995	-2.21763	-0.98244
2/27/14 10:30 AM	3.53073	4.767625	2.5	-2.26763	-1.03073
2/27/14 11:30 AM	3.529022	4.767625	2.45000005	-2.31762	-1.07902
2/27/14 12:30 PM	3.527316	4.767625	2.3499999	-2.41763	-1.17732
2/27/14 1:30 PM	3.525614	4.767625	2.3499999	-2.41763	-1.17561

Simulation results, Observed data & Root Mean Square Error (R13 to R12.9)					
Date	**HEC-RAS (DO mg/L)**	**HCIS (DO mg/L)**	**Monitoring Station (DO mg/L)**	**HCIS Residual (DO)**	**HEC-RAS Residual (DO)**
2/27/14 2:30 PM	3.523916	4.767625	2.32999992	-2.43763	-1.19392
2/27/14 3:30 PM	3.522221	4.767625	2.28999996	-2.47763	-1.23222
2/27/14 4:30 PM	3.52053	4.767625	2.22000003	-2.54762	-1.30053
2/27/14 5:30 PM	3.518843	4.767625	2.1400001	-2.62762	-1.37884
2/27/14 6:30 PM	3.517159	4.767625	2.05999994	-2.70763	-1.45716
2/27/14 7:30 PM	3.51548	4.767625	2	-2.76763	-1.51548
2/27/14 8:30 PM	3.513805	4.767625	1.99000001	-2.77762	-1.5238
2/27/14 9:30 PM	3.512134	4.767625	2.08999991	-2.67763	-1.42213
2/27/14 10:30 PM	3.510468	4.767625	2.42000008	-2.34762	-1.09047
2/27/14 11:30 PM	3.508806	4.767625	2.48000002	-2.28762	-1.02881
2/28/14 12:30 AM	3.507149	4.767625	2.56999993	-2.19763	-0.93715
2/28/14 1:30 AM	3.505496	4.767625	2.6500001	-2.11762	-0.8555
2/28/14 2:30 AM	3.503848	4.767625	2.74000001	-2.02762	-0.76385
2/28/14 3:30 AM	3.502206	4.767625	2.75	-2.01763	-0.75221
2/28/14 4:30 AM	3.500569	4.767625	2.70000005	-2.06762	-0.80057
2/28/14 5:30 AM	3.498937	4.767625	2.63000011	-2.13762	-0.86894
2/28/14 6:30 AM	3.49731	4.767625	2.6500001	-2.11762	-0.84731
2/28/14 7:30 AM	3.49569	4.767625	2.78999996	-1.97763	-0.70569
2/28/14 8:30 AM	3.494076	4.767625	2.8900001	-1.87762	-0.60408
2/28/14 9:30 AM	3.492467	4.767625	2.97000003	-1.79762	-0.52247
2/28/14 10:30 AM	3.490865	4.767625	3.0999999	-1.66763	-0.39087
2/28/14 11:30 AM	3.489269	4.767625	3.24000001	-1.52762	-0.24927
2/28/14 12:30 PM	3.48768	4.767625	3.3599999	-1.40763	-0.12768
2/28/14 1:30 PM	3.486098	4.767625	3.51999998	-1.24763	0.033902
2/28/14 2:30 PM	3.484522	4.767625	3.57999992	-1.18763	0.095478
2/28/14 3:30 PM	3.482954	4.767625	3.63000011	-1.13762	0.147046
2/28/14 4:30 PM	3.481393	4.767625	3.55999994	-1.20763	0.078607
2/28/14 5:30 PM	3.47984	4.767625	3.47000003	-1.29762	-0.00984
2/28/14 6:30 PM	3.478293	4.767625	3.44000006	-1.32762	-0.03829
2/28/14 7:30 PM	3.476755	4.767625	3.44000006	-1.32762	-0.03675
2/28/14 8:30 PM	3.475223	4.767625	3.3900001	-1.37762	-0.08522
2/28/14 9:30 PM	3.473699	4.767625	3.21000004	-1.55762	-0.2637
2/28/14 10:30 PM	3.472183	4.767625	2.96000004	-1.80762	-0.51218
2/28/14 11:30 PM	3.470674	4.767625	2.71000004	-2.05762	-0.76067
3/1/14 12:30 AM	3.469173	4.767625	2.55999994	-2.20763	-0.90917
3/1/14 1:30 AM	3.46768	4.767625	2.49000001	-2.27762	-0.97768
3/1/14 2:30 AM	3.466194	4.767625	2.42000008	-2.34762	-1.04619
3/1/14 3:30 AM	3.464716	4.767625	2.36999989	-2.39763	-1.09472
3/1/14 4:30 AM	3.463246	4.767625	2.3499999	-2.41763	-1.11325
3/1/14 5:30 AM	3.461784	4.767625	2.41000009	-2.35762	-1.05178
3/1/14 6:30 AM	3.46033	4.767625	2.45000005	-2.31762	-1.01033
3/1/14 7:30 AM	3.458884	4.767625	2.50999999	-2.25763	-0.94888
3/1/14 8:30 AM	3.457447	4.767625	2.48000002	-2.28762	-0.97745
3/1/14 9:30 AM	3.456017	4.767625	2.44000006	-2.32762	-1.01602
3/1/14 10:30 AM	3.454596	4.767625	2.3599999	-2.40763	-1.0946
3/1/14 11:30 AM	3.453183	4.767625	2.27999997	-2.48763	-1.17318
3/1/14 12:30 PM	3.451779	4.767625	2.19000006	-2.57762	-1.26178
3/1/14 1:30 PM	3.450383	4.767625	2.16000009	-2.60762	-1.29038
3/1/14 2:30 PM	3.448996	4.767625	2.11999989	-2.64763	-1.329
3/1/14 3:30 PM	3.447617	4.767625	2.07999992	-2.68763	-1.36762
3/1/14 4:30 PM	3.446247	4.767625	1.99000001	-2.77762	-1.45625
3/1/14 5:30 PM	3.444886	4.767625	1.87	-2.89762	-1.57489
3/1/14 6:30 PM	3.443533	4.767625	1.70000005	-3.06762	-1.74353
3/1/14 7:30 PM	3.44219	4.767625	1.53999996	-3.22763	-1.90219
3/1/14 8:30 PM	3.440856	4.767625	1.15999997	-3.60763	-2.28086
3/1/14 9:30 PM	3.43953	4.767625	2.74000001	-2.02762	-0.69953
3/1/14 10:30 PM	3.438214	4.767625	2.78999996	-1.97763	-0.64821
3/1/14 11:30 PM	3.436907	4.767625	2.83999991	-1.92763	-0.59691
3/2/14 12:30 AM	3.435616	4.767625	2.9000001	-1.86762	-0.53562
3/2/14 1:30 AM	3.434339	4.767625	2.94000006	-1.82762	-0.49434
3/2/14 2:30 AM	3.433077	4.767625	3.44000006	-1.32762	0.006923
3/2/14 3:30 AM	3.43183	4.767625	3.0999999	-1.66763	-0.33183
3/2/14 4:30 AM	3.430598	4.767625	3.20000005	-1.56762	-0.2306
3/2/14 5:30 AM	3.42938	4.767625	3.53999996	-1.22763	0.11062
3/2/14 6:30 AM	3.428177	4.767625	3.66000009	-1.10762	0.231823
3/2/14 7:30 AM	3.426989	4.767625	3.55999994	-1.20763	0.133011
3/2/14 8:30 AM	3.425816	4.767625	3.73000002	-1.03762	0.304184
3/2/14 9:30 AM	3.424657	4.767625	3.88000011	-0.88762	0.455343
3/2/14 10:30 AM	3.423513	4.767625	4.05000019	-0.71762	0.626487
3/2/14 11:30 AM	3.422384	4.767625	4.46999979	-0.29763	1.047616
3/2/14 12:30 PM	3.421269	4.767625	4.26000023	-0.50762	0.838731
3/2/14 1:00 PM	3.420169	4.767625	4.63999987	-0.12763	1.219831
3/2/14 2:00 PM	3.419084	4.767625	4.82000017	0.052375	1.400916
3/2/14 3:00 PM	3.418013	4.767625	5.44999981	0.682375	2.031987
3/2/14 4:00 PM	3.416957	4.767625	4.75	-0.01762	1.333043
3/2/14 5:00 PM	3.415916	4.767625	5.48000002	0.712375	2.064084
3/2/14 6:00 PM	3.414889	4.767625	5.28999996	0.522375	1.875111
3/2/14 7:00 PM	3.413877	4.767625	5.05000019	0.282375	1.636123
3/2/14 8:00 PM	3.412879	4.767625	4.86999989	0.102375	1.457121
3/2/14 9:00 PM	3.411896	4.767625	4.48999977	-0.27763	1.078104
3/2/14 10:00 PM	3.410927	4.767625	4.34000015	-0.42762	0.929073
3/2/14 11:00 PM	3.409972	4.767625	4.13000011	-0.63762	0.720028
3/3/14 12:00 AM	3.409032	4.767625	2.5999999	-2.16763	-0.80903
3/3/14 1:00 AM	3.408106	4.767625	2.44000006	-2.32762	-0.96811
3/3/14 2:00 AM	3.407195	4.767625	2.56999993	-2.19763	-0.8372
3/3/14 3:00 AM	3.406298	4.767625	2.63000011	-2.13762	-0.7763
3/3/14 4:00 AM	3.405416	4.767625	2.6500001	-2.11762	-0.75542
3/3/14 5:00 AM	3.404549	4.767625	2.68000007	-2.08762	-0.72455
3/3/14 6:00 AM	3.403697	4.767625	2.71000004	-2.05762	-0.6937
3/3/14 7:00 AM	3.402859	4.767625	2.70000005	-2.06762	-0.70286

Simulation results, Observed data & Root Mean Square Error (R13 to R12.9)					
Date	**HEC-RAS (DO mg/L)**	**HCIS (DO mg/L)**	**Monitoring Station (DO mg/L)**	**HCIS Residual (DO)**	**HEC-RAS Residual (DO)**
3/3/14 8:00 AM	3.402036	4.767625	2.68000007	-2.08762	-0.72204
3/3/14 9:00 AM	3.401229	4.767625	2.67000008	-2.09762	-0.73123
3/3/14 10:00 AM	3.400437	4.767625	2.61999989	-2.14763	-0.78044
3/3/14 11:00 AM	3.39966	4.767625	2.6099999	-2.15763	-0.78966
3/3/14 12:00 PM	3.398898	4.767625	2.58999991	-2.17763	-0.8089
3/3/14 1:00 PM	3.398151	4.767625	2.58999991	-2.17763	-0.80815
3/3/14 2:00 PM	3.39742	4.767625	2.58999991	-2.17763	-0.80742
3/3/14 3:00 PM	3.396705	4.767625	2.54999995	-2.21763	-0.84671
3/3/14 4:00 PM	3.396005	4.767625	2.50999999	-2.25763	-0.88601
3/3/14 5:00 PM	3.39532	4.767625	2.45000005	-2.31762	-0.94532
3/3/14 6:00 PM	3.394652	4.767625	2.46000004	-2.30762	-0.93465
3/3/14 7:00 PM	3.393998	4.767625	2.45000005	-2.31762	-0.944
3/3/14 8:00 PM	3.393361	4.767625	2.44000006	-2.32762	-0.95336
3/3/14 9:00 PM	3.39274	4.767625	2.99000001	-1.77762	-0.40274
3/3/14 10:00 PM	3.392134	4.767625	3.02999997	-1.73763	-0.36213
3/3/14 11:00 PM	3.391544	4.767625	3.0999999	-1.66763	-0.29154
3/4/14 12:00 AM	3.39097	4.767625	3.25	-1.51763	-0.14097
3/4/14 1:00 AM	3.390411	4.767625	3.33999991	-1.42763	-0.05041
3/4/14 2:00 AM	3.389869	4.767625	3.41000009	-1.35762	0.020131
3/4/14 3:00 AM	3.389342	4.767625	3.49000001	-1.27762	0.100658
3/4/14 4:00 AM	3.38883	4.767625	3.6099999	-1.15763	0.22117
3/4/14 5:00 AM	3.388335	4.767625	3.69000006	-1.07762	0.301665
3/4/14 6:00 AM	3.387855	4.767625	3.77999997	-0.98763	0.392145
3/4/14 7:00 AM	3.38739	4.767625	3.88000011	-0.88762	0.49261
3/4/14 8:00 AM	3.386941	4.767625	3.99000001	-0.77762	0.603059
3/4/14 9:00 AM	3.386507	4.767625	4.13000011	-0.63762	0.743493
3/4/14 10:00 AM	3.386088	4.767625	4.32000017	-0.44762	0.933912
3/4/14 11:00 AM	3.385685	4.767625	4.80999994	0.042375	1.424315
3/4/14 12:00 PM	3.385297	4.767625	7.76000023	2.992375	4.374703
3/4/14 1:00 PM	3.384924	4.767625	5.05999994	0.292375	1.675076
3/4/14 2:00 PM	3.384566	4.767625	5.26999998	0.502375	1.885434
3/4/14 3:00 PM	3.384223	4.767625	6.63999987	1.872375	3.255777
3/4/14 4:00 PM	3.383895	4.767625	5.40999985	0.642375	2.026105
3/4/14 5:00 PM	3.383583	4.767625	6.46000004	1.692375	3.076417
3/4/14 6:00 PM	3.383285	4.767625	6.17000008	1.402375	2.786715
3/4/14 7:00 PM	3.383001	4.767625	5.07000017	0.302375	1.686999
3/4/14 8:00 PM	3.382733	4.767625	5.26000023	0.492375	1.877267
3/4/14 9:00 PM	3.382479	4.767625	5.36999989	0.602375	1.987521
3/4/14 10:00 PM	3.382241	4.767625	4.51999998	-0.24763	1.137759
3/4/14 11:00 PM	3.382016	4.767625	5.21000004	0.442375	1.827984
3/5/14 12:00 AM	3.381807	4.767625	2.42000008	-2.34762	-0.96181
3/5/14 1:00 AM	3.381611	4.767625	2.45000005	-2.31762	-0.93161
3/5/14 2:00 AM	3.381431	4.767625	2.47000003	-2.29762	-0.91143
3/5/14 3:00 AM	3.381264	4.767625	2.53999996	-2.22763	-0.84126
3/5/14 4:00 AM	3.381113	4.767625	2.69000006	-2.07762	-0.69111
3/5/14 5:00 AM	3.380975	4.767625	2.83999991	-1.92763	-0.54098
3/5/14 6:00 AM	3.380852	4.767625	2.86999989	-1.89763	-0.51085
3/5/14 7:00 AM	3.380742	4.767625	2.76999998	-1.99763	-0.61074
3/5/14 8:00 AM	3.380647	4.767625	2.75	-2.01763	-0.63065
3/5/14 9:00 AM	3.380567	4.767625	2.74000001	-2.02762	-0.64057
3/5/14 10:00 AM	3.3805	4.767625	2.72000003	-2.04762	-0.6605
3/5/14 11:00 AM	3.380447	4.767625	2.72000003	-2.04762	-0.66045
3/5/14 12:00 PM	3.380408	4.767625	2.72000003	-2.04762	-0.66041
3/5/14 1:00 PM	3.380383	4.767625	2.74000001	-2.02762	-0.64038
3/5/14 2:00 PM	3.380373	4.767625	2.67000008	-2.09762	-0.71037
3/5/14 3:00 PM	3.380375	4.767625	2.67000008	-2.09762	-0.71037
3/5/14 4:00 PM	3.380392	4.767625	2.77999997	-1.98763	-0.60039
3/5/14 5:00 PM	3.380422	4.767625	2.8499999	-1.91763	-0.53042
3/5/14 6:00 PM	3.380466	4.767625	2.71000004	-2.05762	-0.67047
3/5/14 7:00 PM	3.380524	4.767625	2.66000009	-2.10762	-0.72052
3/5/14 8:00 PM	3.380595	4.767625	0.31999999	-4.44763	-3.0606
3/5/14 9:00 PM	3.38068	4.767625	0.30000001	-4.46762	-3.08068
3/5/14 10:00 PM	3.380778	4.767625	0.25999999	-4.50763	-3.12078
3/5/14 11:00 PM	3.380889	4.767625	0.30000001	-4.46762	-3.08089
RMSE				**1.693**	**1.605**

ANNEXTURE A

CERTIFICATE OF ACCREDITATION

In terms of section 22(2) (b) of the Accreditation for Conformity Assessment, Calibration and Good Laboratory Practice Act, 2006 (Act 19 of 2006), read with sections 23(1), (2) and (3) of the said Act, I hereby certify that:-

ETHEKWINI WATER AND SANITATION SCIENTIFIC SERVICES

Facility Accreditation Number: **T0372**

is a South African National Accreditation System accredited Testing laboratory provided that all SANAS conditions and requirements are complied with

This certificate is valid as per the scope as stated in the accompanying schedule of accreditation Annexure "A", bearing the above accreditation number for

CHEMICAL AND MICROBIOLOGY ANALYSIS

The facility is accredited in accordance with the recognised International Standard

ISO/IEC 17025:2005

The accreditation demonstrates technical competency for a defined scope and the operation of a laboratory quality management system

While this certificate remains valid, the Accredited Facility named above is authorised to use the relevant SANAS accreditation symbol to issue facility reports and/or certificates

Mr R Joslas
Chief Executive Officer

Effective Date: 30 April 2013
Certificate Expires: 02 May 2018

SCHEDULE OF ACCREDITATION

Facility Number: T0372

Permanent Address of Laboratory: eThekwini Water and Sanitation Scientific Services Halifax Road Pinetown Durban	**Technical Signatories:** Ms SAF Jackson Mr S Maqubela (Micro only)
Postal Address: P O Box 1038 Durban 4000	**Nominated Representative:** Ms B Kunene
Tel: (031) 311-8003 Fax: (031) 311-8003 E-mail: betty.kunene@durban.gov.za	Issue No.: 09 Date of Issue: 31 July 2013 Expiry Date: 02 May 2018

Materials / Products Tested	Type of Tests / Properties Measured, Range of Measurement	Standard Specifications, Equipment / Technique Used
CHEMISTRY		
Testing of water samples: **Industrial water** **Sewage outfalls** **Trade Effluent** **Sea water** **Swimming pool water** **Surface water** **Drinking water**	pH and Electrical Conductivity by potentiometric determination	M-C-001 & M-C-009
Drinking water **Sea water** **Swimming pool water** **Surface water**	Turbidity by nephelometry	M-C-013
Surface water **Industrial water** **Trade Effluent** **Sewage outfalls**	Chemical oxygen demand (COD) by Microware digestion and Automatic Titration	M-C-011
Surface water **Industrial water** **Trade Effluent** **Sewage outfalls**	Discreet analyser, using Aquachem Chloride (Cl) Ammonia (NH_4) Nitrate (NO_3) + Nitrate (NO_2) Orthophosphate (PO_4) Sulphate (SO_4)	 M-C-029 M-C-032 M-C-030 M-C-031 M-C-028

Original Date of Accreditation: 03 May 2008

Field Manager